How carbon emission prices accelerate net zero: Evidence from China's coal-fired power plants

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This project is funded by the National Key R&D Program of China (2016YFA0602604) and the National Natural Science Foundation of China (7224100119, 72140001).

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ABSTRACT: China produced over half the world’s coal-fired power capacity. Using a recent and comprehensive dataset of 1269 Chinese coal-fired power plants from 2009 to 2019, this paper provides empirical evidence of the impact of China’s carbon trading pilot program on emissions regulation. Results show the significant potential for emissions intensity reduction due to increasing carbon prices, especially for low-risk, low-efficiency but high-cost plants, particularly those in China’s midland and western regions. Rising marginal abatement costs and accelerated depreciation from carbon prices may encourage utilities to retire high-emission power plants sooner than originally planned, leading to lower emissions intensity. The average retirement years of China’s power plants can be shortened by 1.8001 and 1.6862 years under R2CUT and R2LUMP scenarios, respectively, as Cao et al. (2016). This study offers new insights into the impact of carbon prices on power plants and has important policy implications.

Key words**:** Carbon emission price; carbon emission intensity; marginal abatement cost; accelerated depreciation; net-zero retirement; coal-fired power plants

1. Introduction

In 2021, global carbon dioxide (CO2) emissions reached an all-time high of 15.3 billion tonnes, with coal contributing to over 40% of the overall growth (IEA, 2022a). Therefore, phasing out all coal-fired power by 2040 is crucial to meet the Paris Agreement and prevent catastrophic climate change (Goh et al., 2018; Tong et al., 2019; IEA, 2021).

China is the top emitter of carbon and energy consumer, largely due to its abundance of coal and limited access to gas and oil. With 95% of its fossil energy reserves being coal and 65% of its electricity generated from coal-fired power plants (China's National Bureau of Statistics, 2022), its emission intensity is higher than the world average (IEA, 2022b). The power sector alone accounts for 44% of China's CO2 emissions from fossil-fuel combustion (Shan et al., 2020). However, to reach its low-carbon goals, reducing emissions from coal-fired power plants is crucial.

To manage carbon emissions, China has implemented a strategy of retiring old and less efficient coal units for every new coal capacity addition, maintaining zero net coal capacity growth. Despite these efforts, China continues to build new coal capacity for various reasons, including job creation, boosting local economies, integrating renewables, and meeting heating demand while improving power plant efficiency. In 2021, China started construction on 33 GW of new coal-fired power generation, which was three times more than the rest of the world combined, according to Reuters (Person and Stanway, 2022).

Managing the existing coal-fired power fleet is critical for China's clean energy transition, but the number of new coal-fired power plants is not declining. While China has pledged to reach carbon neutrality by 2060, presenting a significant challenge in decarbonizing its many coal-fired power plants, particularly the younger ones, the number of new-built coal-fired power plants in China still increased from 78 in 2017 to 85 in 2019, as shown in **Fig. 1**.

Regulations and market-based measures can effectively reduce CO2 emissions in the medium to long term (Hu et al., 2020). The emissions trading system (ETS) is regarded as the effective tools to incentivize low-carbon transitions by internalizing the external costs of CO2. China's ETS, which includes over 2000 emitters in the power sector with a combined 4 billion tons of CO2, started as pilots in 2013 and has since unified into a national program in 2021. As coal-fired power plants are the primary focus of the ETS, China's improved monitoring through the ETS pilots will lead to better emissions data and overall efficient management of energy use. The output-based allowance allocation and benchmark system will increase the efficiency of existing coal-fired power plants. In the short term, the ETS encourages high-emission coal plants to reduce CO2 emissions by investing in low-carbon technologies or burning higher-quality coal. It also incentivizes companies to shift generation to more efficient power plants. In the long term, the ETS will motivate stakeholders to shift their investments to supercritical and ultra-supercritical plants rather than the traditional ones (IEA, 2020).

Studies have shown that the ETS reduces carbon emissions, improves energy efficiency and fuel switch, drives technological innovation, reduces pollution, and boosts economic growth (Cui et al., 2021; Yang et al., 2022; Zhu et al., 2022; Tan et al., 2022; Chen et al., 2021; Liu et al., 2021; Qi et al., 2021). However, literature on ETS's impact on coal-fired power plants is rather limited, with a focus on industry-level analysis, due to the difficulty of accessible data (Liu et al., 2018; Zhao et al., 2018). Further research is needed to examine how power plants can improve efficiencies and reduce emissions under ETS mechanisms.

The studies by Wu and Wang (2022) and (Wu, 2022) inspired our paper to further explore the impact of carbon prices under ETS on the emission and efficiency of power plant. **Fig. 2** shows average carbon emission prices in eight Chinese ETS pilots since 2013, varying across regions. Beijing has the highest average price at 58.45 CNY/CO2ton and Chongqing has the lowest at 17.76 CNY/CO2ton (3.29 times difference). The price in regions also fluctuates over time. For example, Beijing's price doubled to 87.13 CNY/CO2ton in 2020 from 50.92 CNY/CO2ton in 2017 and then dropped to 50.82 CNY/CO2ton; Shanghai's price dropped from 36.34 CNY/CO2ton in 2014 to 11.26 CNY/CO2ton in 2016 and then increased to 40.48 CNY/CO2ton in 2019. It is obvious that there is a considerable sensitive variation of carbon emission price across time and regions of ETS pilots, and the carbon price in China still has significant upward room, which makes the impact of the carbon price on power plants close to a positive linear relationship. The above observed facts create feasible conditions for us to regard the ETS as a quasi-natural experiment and carry out statistical inference in detail.

To assess the effectiveness of China's eight regional ETS pilots on carbon pricing, we will track the impact of the policy on a selected group of coal-fired power plants over time. We'll look for changes in these plants after the policy took effect. To do this, we will use a staggered difference-in-differences (DID) identification framework, which views the ETS pilot roll-out as a quasi-natural experiment. This framework will help us examine the relationship between the ETS carbon prices and the shift in emission intensity of the power plants. The major contributions of this paper are as follows: 1) A novel micro-level dataset of 1269 coal-fired power plants, compiled from TransitionZero (2021) and province-level economic indicators from 2009 to 2019, allows for direct estimation of plant-level effects rather than at the province or sector level. 2) This paper is among the first to examine the impact of rising carbon transaction prices on carbon emission intensity of ETS-regulated plants and provides empirical evidence for policymaking. 3) This study extends Cao et al. (2021) by examining the impact of carbon emission price fluctuations on operational revenues, short run marginal cost (SRMC) and long run marginal cost (LRMC) of power plants. This paper also considers the mechanisms for marginal abatement costs (MAC) and accelerated depreciation driven by carbon prices that may lead to a lower emissions intensity of power plant and bridging the gap between theory and empirical research. 4) This paper also predicts the expected changes of net-zero retirement years of coal-fired power plants under varying carbon price scenarios.

The main findings of this paper are as follows: 1) The emission intensity will be reduced by 0.0095 CO2 per kilowatt-hour, or 0.1023% of the average, if local carbon emission prices of ETS pilots increase by 1%. And under the assumption that carbon prices remain at their highest recorded level, the average emission intensity of power plants could decrease by 18.86%. 2) Our estimation is robust through various model specifications and excluding confounding factors, and the influence of emissions intensity reduction by increasing carbon prices is more profound for low-risk, low-efficiency but high-cost power plants, particularly those in China's midland and western regions. 3) The improved efficiency will not be at the expense of output. A 1% increase in carbon price leads to a decrease of approximately 5.03 and 7.52 \$/MWh in SRMC and LRMC, representing 11.1% and 15.3% of their means, respectively. The carbon price's effect on a power plant's assets and investment structure is more significant in the long term rather than in the short term. 4) Rising MAC and accelerated depreciation driven by climbing carbon prices may encourage utilities to retire high-emission power plants sooner than originally planned, leading to lower emissions intensity. 5) The average retirement years of China's power plants can be shortened by 1.8001 and 1.6862 years under R2CUT and R2LUMP scenarios, respectively, as Cao et al. (2016). The research findings provide new understanding of emission intensity changes in China's coal-fired power plants caused by carbon prices of ETS, which have significant implications for policymakers as China strives for tighter climate action and carbon neutrality by 2060.

The remainder of this paper is organized as follows: Section 2 presents the relevant literature and then put forward the hypotheses, Section 3 describes the econometrics identification strategy as well as the source of data, followed by the empirical results in Section 4. The last section concludes the paper with policy implications.

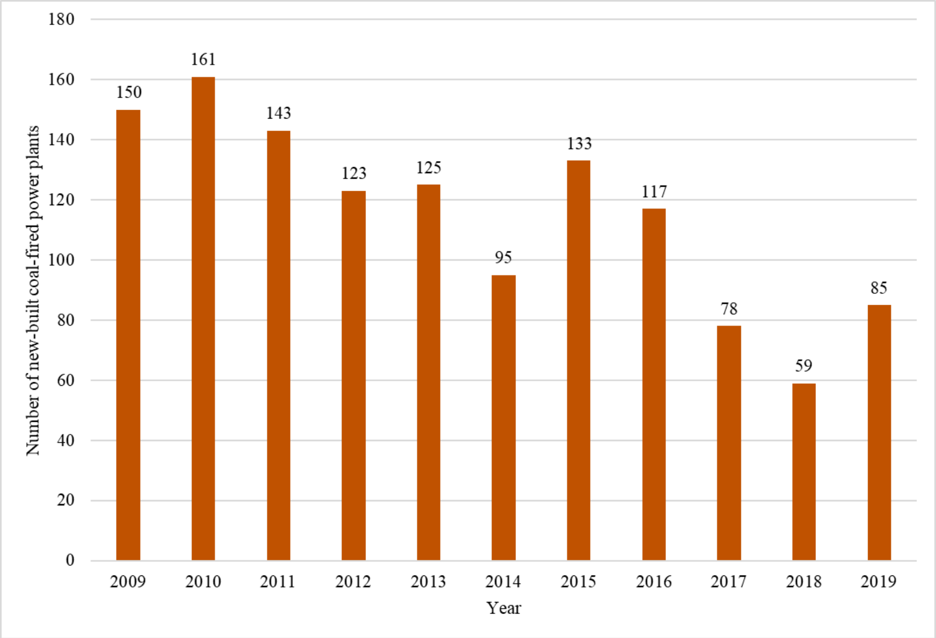

Figure 1. The number of new-built coal-fired power plants in China between 2009 and 2019.

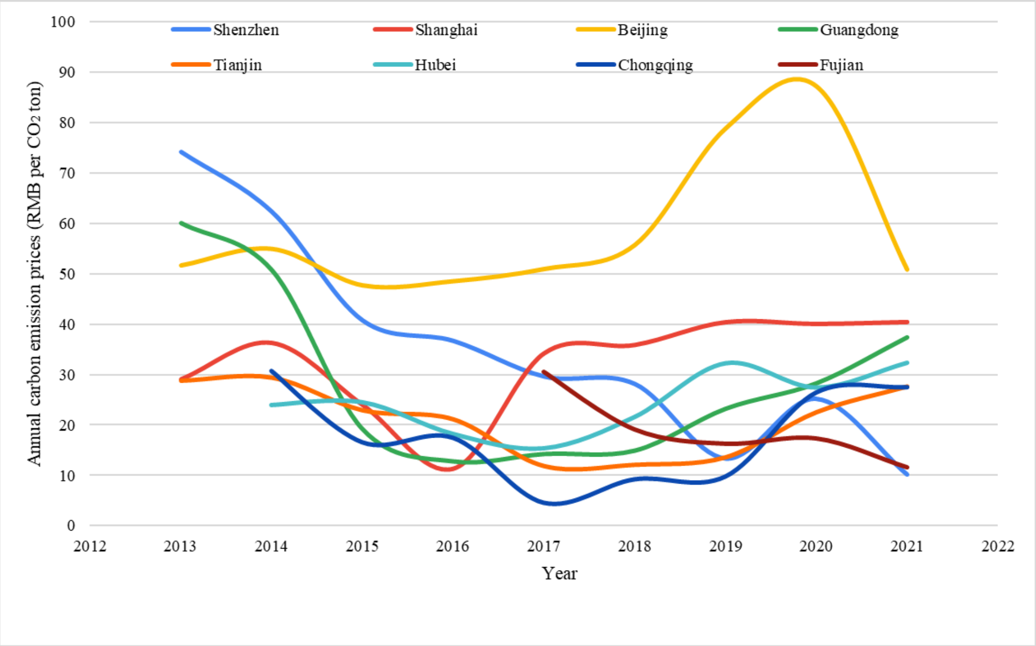

Figure 2. The annual carbon emission prices across China's ETS pilots between 2013 and 2021.

2. Conceptual analysis and hypotheses

2.1. Impact of carbon prices on the emission intensity of power plants.

Emerging studies show that the effects of ETS on regulated firms and regions include reduced carbon emissions (Cui et al., 2021; Yang et al., 2022), improved energy efficiency and fuel switching (Zhu et al., 2022; Tan et al., 2022), technological innovation (Chen et al., 2021), reduced environmental pollution (Liu et al., 2021), economic development (Qi et al., 2021), better financial performance (Yu et al., 2022), and changes in asset structure (Dong et al., 2022). Similar impact factors and channels also apply to coal-fired power plants, despite limited research in this area.

Carbon pricing can effectively reduce the carbon intensity of power plants. Firstly, the carbon market's quota exchange system creates a carbon emission price that leads to higher electricity prices through the Carbon Cost Pass-through Phenomenon. In response, coal-fired power plants adopt emission reduction technologies to mitigate the impact of the rising carbon price. This shift results in a reduction of high-carbon energy sources like fossil fuels and promotes conscious energy planning and consumption, ultimately reducing carbon emissions. The increased carbon price also impacts the cost of electricity for end users, encouraging them to reduce their carbon footprint. (Brouwers et al., 2018; Frondel and Schubert, 2021; Kim and Bae, 2022).

Secondly, the encouragement of clean technology innovation and implementation in power plants is backed by the increasing cost of electricity generation. This is exemplified by the shift in research and development towards multi-source power plants that prioritize the use of renewable energy sources over traditional, polluting sources like coal. As clean technology continues to spread, the price of coal-fired power generation will increase, pushing inefficient and outdated coal-fired units out of the market and making room for cleaner and more efficient alternatives (Cao et al., 2021).

Thirdly, carbon allowances have significant financial attributes. By putting a monetary value on carbon emissions, power plants have the opportunity to offset their impact. This aligns with basic principles of energy economics, where the lower the cost of producing electricity, the more competitive the plant becomes. Carbon finance can also act as a form of diversifying a power plant's energy portfolio, allowing them to reconfigure their energy mix and reduce the overall cost of electricity generation, even in uncertain market conditions. Furthermore, the development of the carbon trading market brings financial derivatives such as investment value, transaction demand, and liquidity to the electricity generation sector, generating attractive risk-adjusted returns that may attract investment from other stakeholders interested in clean energy. (Chevallier, 2009; Koch, 2014; Leitao et al., 2021; Luo et al., 2021).

Generally speaking, regional ETS pilots provide a rich set of variations that enable us to examine the impact of carbon market design and its effect on reducing emissions from coal-fired power plants. This has not been thoroughly explored before. The first hypothesis to be tested is as follows.

H1. *The carbon emissions intensity of power plants regulated by the ETS will decrease as carbon transaction prices rise.*

2.2. Impact of carbon prices on operational revenues and costs of power plants.

Is increased carbon efficiency resulting in decreased output due to tighter carbon transaction prices? Cao et al. (2021) found no correlation between the carbon ETS and the coal efficiency of ETS-supervised power plants. Rather, reduction is achieved through reduced electricity production and energy consumption. However, the validity of this conclusion may be questioned, as there has been significant changes in energy consumption portfolios (Mu et al., 2018).

Marginal cost of production is crucial for the efficient and profitable operation of power plants and carbon prices affect the marginal cost of power plants by internalizing the external costs of carbon emissions into the cost of production. When a carbon price is introduced, power plants must pay a fee for each ton of carbon dioxide they emit. This fee increases the cost of production and raises the marginal cost of power generation. As carbon prices increase, the cost of emitting carbon also elevates, leading to an increase in the marginal cost of producing electricity. This rise in marginal cost can incentivize power plants to shift towards cleaner production methods, such as using renewable energy sources, in order to reduce their carbon emissions and avoid the cost of paying for carbon permits (Dong et al., 2022). In the long-term, the implementation of a carbon pricing scheme may result in changes in the cost structure of a power plant, affecting both SRMC (which includes fuel and variable operations costs) and LRMC (which includes SRMC, fixed operations, and maintenance costs) (Wang et al., 2018).

In a nutshell, the optimization and diminution of production cost through cleaner methods can improve plant profitability and reduce total emissions while maintaining the “affordability and reliability” of electricity generation. These insights support the hypothesis that energy efficiency can lead to both economic benefits and environmental improvements.

H2*. Tighter carbon transaction prices can improve plant profitability by reducing both SRMC and LRMC.*

2.3. Channels for marginal abatement costs and accelerated depreciation

Through enforcing stricter operating standards and upgrading equipment quality control, ETS-regulated power plants have achieved a notable decrease in carbon emission intensity, not merely at the cost of falling power generation. The connection between this reduction and the rise of carbon prices highlights the dynamic economic principle at play, leading us to the crucial question: what drives this transmission mechanism?

Firstly, a rising carbon price increases the financial incentive for power plants to reduce their carbon emissions. As a result, power plants will start to explore ways to reduce emissions and shift to more efficient and cleaner energy sources. However, reducing emissions involves costs, and as the emissions decrease, it becomes more and more expensive to reduce each additional unit of emissions, which is reflected in the rising MAC (Xue et al., 2021; Jiang et al., 2022). The MAC curve provides a cost-effectiveness evaluation of emissions reduction options and helps power plants determine the most cost-effective way to reduce emissions. The power plants can choose to reduce emissions in the short-term by investing in low-cost technologies or they can take a longer-term approach and invest in more expensive but advanced technologies that will reduce emissions more effectively (Ellerman and Decaux, 1998). As the carbon price increases, power plants face a financial incentive to reduce emissions, and the rising MAC helps determine the most cost-effective way to do so, ultimately leading to a reduction in the carbon emission intensity of the power sector (Mo et al., 2021).

Secondly, carbon prices can reduce the carbon emission intensity of power plants through the acceleration of depreciation of power plant assets. Accelerated depreciation allows power plants to write off their costs at a faster rate than under normal depreciation methods. When a carbon price is implemented, utilities may choose to retire their older, high-emission power plants earlier than originally planned due to the increased cost of emissions. This can be achieved through accelerated depreciation, which allows the company to write off the value of the retired asset at a faster rate, thereby reducing the company’s taxable income. As a result, the accelerated depreciation incentivizes the retirement of high-emitting power plants, making it more economically attractive to deploy low-carbon alternatives, and invest in newer, cleaner technologies, which in turn leads to a decrease in the carbon intensity of the power sector (Lehr, 2019). Therefore, we propose testing the third hypothesis.

***H_3**: The increase of carbon prices will drive a decrease in emissions intensity of power plants, due to stricter MAC limits and accelerated depreciation of fixed assets.*

2.4. Transformation effect of carbon prices on net-zero retirement

All coal-fired power generation should be phased out by 2040 in order to comply with the Paris Agreement and prevent catastrophic climate change (IEA, 2021). As a result, since existing coal plants are increasingly at risk of early retirement, new coal facilities are incompatible with global warming goals. According to the analysis above, rising carbon prices lead to increased MAC and accelerated depreciation, causing utilities to retire high-emission power plants ahead of schedule due to increased emission costs, which facilitates China's transition to clean energy.

Firstly, it makes sense that the rational decision of power plants to retire is based on the relative importance of the marginal advantage an entity derives from a decision and also its marginal cost, which is expressed in the opportunity cost. The fair value of a carbon allowance is determined by the cost of emission reductions in the future, discounted back in real terms, when the ETS has an absolute cap. As a result, after entering the ETS pilot programs, the lifespan of coal-fired power plants with large carbon emissions will be drastically shortened because the inefficient ones will be unable to finally generate enough revenue to cover their expenditures due to the tight MAC requirements (Wang et al., 2021; Nhuchhen et al., 2022).

Secondly, from an ex-ante perspective, carbon pricing plays a role in individual decision as well. To be specific, they send a signal to power plants to adjust their expectations by boosting the cost of energy from fossil fuels because they generate significant amounts of carbon dioxide when burned. The sooner local governments halt the building of ineffective power plants, the lower the cost of emission reduction will be in the long run; specifically, halting the development of ineffective projects can prevent a large amount of investment from being left stranded. The power plants that should be authorized for construction, in contrast, are virtually always those with clean technologies and simple access to netzero emissions. As a result, the tight carbon price often favors the viability of gradually retiring power plants before beginning the benign progression toward net-zero transformation (Kefford et al., 2018; Springer et al., 2022). We investigate the following hypothesis.

***H4**. Carbon price will accelerate the net-zero retirement of coal-fired power plants.*

3. Research design

3.1. Data and variables

The research uses two datasets: China's Plant Information Dataset from TransitionZero (2021) and China Provincial Statistical Yearbook (2009–2019). The team of TransitionZero (2021) uses satellite images and published generation data to train machine learning models and estimate detailed operational information (e.g. capacity, generation, emissions, costs, revenues) for coal-fired power plants. We merged two datasets, using firm coordinates and operating year, to create a final balanced panel of 1269 power plants with data from 2009 to 2019. To avoid data omission errors, we also included control variables based on the theories from previous literature, from China Provincial Statistical Yearbook.

Our focus is the emission intensity of power plants, measured as carbon emissions per kilowatt-hour, or the ratio of carbon emissions to net generation. This indicator prioritizes electricity output over carbon emissions. The generation and carbon emission data are from TransitionZero (2021). We aggregate this data to the provincial level and compare it with annual generation data from China's National Bureau of Statistics. The accuracy varies between 5% and 15%. Additionally, this article calculates carbon emissions by converting standard coal consumption to carbon emissions for each province using coefficients from IPCC (2006) and China's National Development and Reform Commission (2007). The two carbon emission datasets have a similar trend and regional distribution.

Our policy variable is the ETS, which we gather from official documents. China first proposed a carbon ETS market in 2011 to reduce emissions, and launched pilot programs in five provinces and three cities in 2013. Guangdong, Beijing, Shenzhen, Tianjin, and Shanghai were the first to implement local ETS pilots, followed by Hubei and Chongqing in 2014, and Fujian in 2016. Differ from the numerous literature which treats ETS as a policy shock at mere, we refer to Wu and Wang (2022) and Wu (2022), and establish a triple interactive term ETS × POST × price to capture the effect of carbon prices of ETS. Particularly, ETS and POST are binary variables indicating whether the region is regulated under ETS and whether the pilots have been implemented. The price is the annual average carbon emission price of ETS pilots, integrated and obtained from the Wind-Financial Terminal, reflecting the supply and demand of carbon allowances.

This study thoroughly examines power plants and includes additional dependent variables. To test H2, we include near-term and long-term run marginal costs, including fuel, variable operations, fixed operations, and maintenance costs. To test H3, we use MAC, calculated as the value-adjusted levelized costs of electricity for zero-carbon alternatives such as solar photovoltaics (PV) or onshore wind. To test H4, we use the expected net-zero retirement time for plants, based on demand constraint, risk assessment, and close capacity, and calculated in accordance with China's net-zero policy goal. All indicators are from TransitionZero (2021).

On the basis of the theoretical analysis above and the classical models of IPAT and STIRPAT and relevant literature: 1) the stage of development. Most of the studies have reported that economic growth, industrial structure, and population urbanization are substantial sources of carbon emission (Waheed et al., 2019; Wang and Wang, 2021); 2) technology and research support. Investment in fixed assets and government spending are crucial for advancing low-carbon technologies and infrastructure, which reduces emissions and supports a sustainable economy. Conversely speaking, subsidies for fossil fuel production and hinder progress towards a low-carbon future (Wang and

Li, 2019; Jin and Han, 2021); 3) energy substitution. Energy substitution refers to the process of replacing one energy source with another which can have a significant impact on carbon emissions, depending on the energy sources being replaced and replaced with. And coal and natural gas are both considered fossil fuels but exist in a competitive relationship (Biresselioglu and Yelkenci, 2016); 4) carbon sinks. The forests are natural systems that provide a function of "carbon sink" and absorb a net 7.6 billion metric tons of CO2 annually, about 1.5 times more than its releases, according to World Resources Institute (Harris and Gibbs, 2021). Thusly the local carbon sink capacity needs to be excluded in our empirical estimation to avoid confounding effect. These data are all from China Provincial Statistical Yearbook between 2009 and 2019, and their detailed definition and descriptive statistics are shown in **Tables 1 and 2**.

3.2. Econometric model

Based on the need to compare the impact of ETS pilots on a specific group of power plants over time. We use China's eight regional ETS pilots as a quasi-natural experiment and employ a staggered DID identification framework to test the hypotheses (Cui et al., 2021; Chen, 2021; Gao et al., 2022). This method involves dividing the study participants into two or more groups and administering the ETS intervention at different times to each group and allows us to compare the results of the ETS intervention on each group, and to observe any changes in these groups over time. This design also allows controlling for any extraneous variables that may impact the results and estimate the causal effect of the treatment or policy more accurately.

$$Y_{i,t}=\alpha+\beta ETS_{i,t}\times POST_{i,t}\times price_{i,t}+\gamma ETS_{i,t}\times POST_{i,t}+\boldsymbol{\theta X}+\lambda_c+\lambda_t+\varepsilon_{i,t} \tag{1}$$

with i and t refer to the plant and year, separately, and the province where the power plant is located is subscripted as c. Our most interested coefficient β weights the impact of carbon prices of ETS on emission intensity of power plants. The interaction of ETS and POST is added to exclude the start effect of ETS pilots to obtain a net real effect. Y is the outcome variables. The selection of control variables $\boldsymbol{X}$ is followed with **Tables 1 and 2**. λ_c is to control for unobservable provincial attributes which are time-invariant, and λ_t is time fixed effect that absorbs annual-specific unobservable. To account for the temporal and spatial distribution of power plants, we cluster standard errors at the provincial level for all regressions. **Table 3** compares mean values across ex-ante and ex-post of the ETS coverage and reveals significant diversity among our main indicators, such as emission intensity and the net-zero retirement time of power plants, while gross and net profitability show opposite shifts. This initial comparison supports our hypotheses and guides our statistical inference.

Table 1

The measurement of main variables.

Classification	Symbol	Definition	Measurement
Outcome variables	CO_2/Gen	Carbon emission per kilowatt-hour	Ratio of carbon emissions on net generation.
Policy variables	*ETS*	Treatment dummies	Equals 1 if the region will be regulated in ETS and 0 otherwise.
	POST	Post dummies	Equals 1 if ETS pilots have been enacted and 0 otherwise.
	ETS×POST	The DID term	Product of ETS and POST.
	Price	The price of carbon emissions	Annual means of carbon-trade price after logarithmicization.
Control variables	*AGDP*	GDP per capita	Proportion of GDP on population.
	URBAN	Urbanization (%)	Proportion of cities where the population resides.
	IND	Industrial structure (%)	Proportion of GDP of non-agricultural industries.
	INV_ENE	Fixed asset investment of energy industry	Ratio of fixed asset investment of energy industry on GDP.
	FIS_ENV	Fiscal expenditure on environmental protection	Ratio of fiscal expenditure on environmental protection on GDP.
	GAS	Total supply of urban natural gas	Total supply of natural gas for urban residents.
	GAS_CON	Total population who consumes natural gas	Total number of populations who consumes natural gas.
	ELE	Total consumption of electricity	Total consumption of urban electricity.
	FOREST	Coverage of forest (%)	Percentage of land that forest cover.
Other variables	*SRMC*	Short run marginal cost ($/MWh)	Summation of fuel cost, variable operations, and maintenance costs (TransitionZero, 2021).
	LRMC	Long run marginal cost ($/MWh)	Summation of SRMC, fixed operations, and maintenance costs (TransitionZero, 2021).
	Gross profitability	Revenues minus SRMC ($/MWh)	Revenues from in-market and out-of-market minus SRMC (TransitionZero, 2021).
	Net profitability	Revenues minus LRMC ($/MWh)	Revenues from in-market and out-of-market minus LRMC (TransitionZero, 2021).
	MAC	Marginal abatement cost ($/tCO$_2$)	Substitution cost based on value-adjusted levelised costs of electricity of either onshore wind or solar PV (TransitionZero, 2021).
	UDV	Undepreciated value ($/MW)	The undepreciated valued, expressed in $/MW (TransitionZero, 2021).
	Net-zero retirement	Expected net-zero retirement year of plants	Retirement year based on China's net-zero policy goal (TransitionZero, 2021).

Table 2

Descriptive statistics of variables.

Variables	Observations	Mean	S.D.	Min.	Max.	Percentiles		Skew.	Kurt.
						1%	99%		
CO_2	1269	1.31	0.89	0.00	4.23	0.05	3.90	0.92	3.70
Gen	1269	0.15	0.11	0.00	0.54	0.01	0.49	1.22	4.39
CO_2*/Gen*	1269	9.25	1.18	0.00	11.30	7.70	11.14	-4.16	32.75
ETS	1269	0.11	0.31	0.00	1.00	0.00	1.00	2.54	7.45
POST	1269	0.03	0.17	0.00	1.00	0.00	1.00	5.68	33.28
ETS×POST	1269	0.03	0.17	0.00	1.00	0.00	1.00	5.68	33.28
Price	1269	0.09	0.53	0.00	4.11	0.00	3.22	5.93	37.20
SRMC	1269	45.32	6.77	0.00	57.37	24.84	56.22	-2.87	18.78
LRMC	1269	49.18	7.62	0.00	81.68	28.88	65.64	-2.10	17.40
Gross profitability	1269	7.30	11.42	-15.75	44.13	-14.60	39.12	0.01	2.59
Net profitability	1269	3.44	11.81	-24.51	40.18	-23.36	27.64	-0.07	2.63
MAC	1269	-27.51	6.55	-55.55	0.00	-41.66	-7.07	0.79	6.77
UDV	1269	458000	78329.32	227000	1920000	323000	608000	5.599	99.537
Net-zero retirement	1269	2033.98	4.08	2027.00	2043.00	2027.00	2041.00	0.01	1.88
AGDP	1269	10.66	0.40	9.30	11.73	9.67	11.53	-0.30	3.19
URBAN	1269	1.27	0.71	0.43	8.36	0.54	3.89	5.57	49.82
IND	1269	11.44	12.04	2.58	152.64	4.04	62.36	7.76	77.85
INV_ENE	1269	1156.54	805.56	0.00	3382.51	0.00	2998.27	0.50	2.42
FIS_ENV	1269	0.01	0.00	0.00	0.04	0.00	0.02	1.90	11.01
GAS	1269	31.76	28.51	0.01	191.85	0.35	124.74	1.78	6.81
GAS_CON	1269	940.22	694.36	10.32	3394.66	32.97	3203.00	1.34	4.52
ELE	1269	2301.38	1425.40	133.77	6695.85	515.25	6218.72	0.92	3.01
FOREST	1269	25.83	15.86	4.20	66.80	4.20	60.00	0.57	2.37

Note: All monetary variables are converted into real on the basis of 2008, and the continuous variables are narrowed down with 1% tail reduction as well.

Table 3

Comparison of mean values across ex-ant & ex-post of ETS covered.

Period	Treatment	CO_2*/Gen*	Gross profitability	Net profitability	Net-zero retirement time
Pre-ETS covered	ETS pilots	9.272358	19.34273	15.91272	2033.96
Post-ETS covered	ETS pilots	8.919485	19.91334	16.1555	2031.778

4. Empirical results

4.1. Baseline estimation

Table 4 presents the baseline results of the impact of carbon prices on plant emission intensity. Columns (1) and (2) present a simple correlation analysis, while columns (3) and (4) add control variables. Take column (4) for instance, the interested estimator is 0.9464, and both economically and statistically significant at 5% and 1% levels, indicating that regulated power plants in ETS pilot provinces can experience a reduction on their emission intensity compared to non-regulated coal-fired power plants in non-ETS pilots. The emission intensity will be reduced by 0.0095 CO2 per kilowatt-hour, or 0.1023% of the average, if local carbon emission prices of ETS pilots increase by 1%. Additionally, under the assumption that carbon prices remain at their highest recorded level, the average emission intensity of power plants could decrease by 18.86%.

Beyond the above, as fixed effects and control variables are added to the econometric model, the explanatory power of the model continues to increase, from 0.003 in column (1) to 0.301 in column (4). This is because fixed effects and control variables allow for a more detailed and accurate analysis of the data, allowing for a better understanding of the underlying relationships and patterns. Additionally, these variables help to control for any potential confounding factors and reduce measurement error, leading to more robust and reliable estimates. Overall, the inclusion of fixed effects and control variables in econometric models can greatly enhance the ability to explain and predict the phenomena under study.

This paper also utilized statistical techniques to conduct residual diagnostics in econometrics, in order to verify the reliability of the model. The residuals were analyzed to ensure that assumptions such as normality, independence, and constant variance were met, and that there were no patterns or outliers present. Additionally, the residuals were used to detect any omitted variable bias through Ramsey's RESET test, heteroskedasticity through Breusch-Pagan test, and multicollinearity. Through this process, the paper was able to establish the validity of the model and demonstrate that the model's estimation can be trusted.

The estimation results of control variables can provide insight into the strength and direction of their effect on the outcome variable. As shown in **Table 4**, economic growth (AGDP), population urbanization (URBAN), and industrial structural upgrading (IND) are factors that can lead to a reduction in the carbon emissions intensity of power plants. Intuitively, economic growth can typically lead to increased investment in clean energy technologies and equipment, while population urbanization may lead to a shift away from heavy industry towards service-based industries, which tend to have lower emissions. Additionally, industrial structural upgrading can tend to improvements in energy efficiency and the increased use of renewable energy sources and help to reduce the carbon footprint of the power industry and contribute to the reduction of overall greenhouse gas emissions. Our results show that the investment in fixed assets on energy industry (INV_ENE), such as equipment and infrastructure, generally does not directly cause changes in the carbon emissions intensity of a power plant. And the increase in government spending on environmental protection (FIS_ENV) led to a rise in carbon emissions intensity of power plants due to the government's investments in environmental protection primarily focus on increasing the use of renewable energy sources, such as wind and solar power, rather than implementing emissions reduction measures at existing fossil fuel-powered power plants. Besides, the demand of natural gas and electricity in city (GAS, GAS_CON and ELE) does not affect the carbon emissions intensity of the plant directly. Lastly, as trees can remove carbon from the atmosphere and offset the emissions produced by power plants. The forest (FOREST) allows power plants to meet emissions reduction targets and comply with regulations while still continuing to operate their facilities.

Table 4

The baseline result of carbon prices on plants' emission intensity.

	(1)	(2)	(3)	(4)
Outcome variable	CO_2/Gen	CO_2/Gen	CO_2/Gen	CO_2/Gen
$ETS \times POST \times price$	-0.1150***	-0.1173**	-0.7298***	-0.9464***
	(0.0384)	(0.0473)	(0.1290)	(0.3329)
$ETS \times POST$			2.8987***	3.6347***
			(0.5803)	(1.2583)
AGDP			-0.0928	-0.2226
			(0.6076)	(0.6822)
URBAN			-1.8300**	-1.0422
			(0.8362)	(1.0088)
IND			-0.0392	-0.0388
			(0.0518)	(0.0505)
INV_ENE			-0.0002	-0.0002
			(0.0002)	(0.0004)
FIS_ENV			29.2941	28.3651
			(44.5531)	(35.0105)
GAS			0.0013	-0.0000
			(0.0034)	(0.0044)
GAS_CON			0.0001	0.0002
			(0.0003)	(0.0003)
ELE			-0.0001	-0.0001
			(0.0002)	(0.0002)
FOREST			-0.0656	-0.1154
			(0.1062)	(0.1290)
_cons	9.2561***	9.2563***	14.8835***	16.3949**
	(0.0792)	(0.0042)	(4.3646)	(6.0354)
Provincial FE	No	Yes	Yes	Yes
Time FE	No	No	No	Yes
N	1269	1269	1269	1269
R^2	0.003	0.110	0.250	0.301

Notes: $p < 0.10$, $p < 0.05$, $p < 0.01$ are displayed with *, **, ***, respectively. FE is the abbreviation for "Fixed effect.". Standard errors are clustered at provincial level for all regressions.

4.2. More robust checks

Propensity score matching with DID (PSM-DID) is a popular econometric method used to estimate the causal effect of an intervention on an outcome of interest, by controlling for a wide range of confounding variables and by comparing changes in the outcome over time between treatment and control groups. And although the eight pilot carbon trading schemes approved by China's central government have been randomly selected to be at varying stages of development with considerable leeway, pilot enterprises are included based on their historical carbon emissions and other characteristics. Therefore, we use PSM-DID to match treatment and control units to reduce selection bias for a stronger causality assessment.

The estimator proposed by Callaway and Sant'Anna (2021) (CS hereafter) allows for multiple periods and variation in treatment timing and maintains parallel trends conditional on covariates. CS's estimator is based on a double robust estimation approach, avoiding the problems with two-way fixed effect of panel data. The advantage of CS's estimator is that it provides various options for aggregating the results of different subgroup DID regressions. In addition to the common approach of analyzing the dynamic effect of a policy based on the timing of events, its Stata package also allows us to calculate the heterogeneity of treatment effects among different subgroups, different years, and the cumulative value of treatment effects over time.

The PSM-DID and CS estimated results are shown in **Table 5**. PSM technique is applied to columns (1) and (2). For each treated power plant, 2 control plants with similar estimated infiltration likelihood based on observed characteristics are selected and we set a caliper threshold of ±0.05 for the difference in propensity scores between treatment and control groups. Columns (3) and (4) use the CS's estimator. It reveals that the estimates obtained through PSM-DID are larger than those obtained through benchmark. This result is likely due to the fact that PSM-DID is able to control for more potential confounding effect of observable characteristics. CS estimation results are larger than benchmark but have less statistical significance. This is due to overcoming drawbacks in two-way fixed effects regressions when treatment timing has multiple periods. In a nutshell, the results of our econometric analysis are consistent with our expectations which show a statistically significant reduction in the carbon emissions intensity of power plants as a causal result of the increase in the carbon price implemented through ETS, reinforcing the validity of our research hypothesis.

Additionally, to eliminate potential biases in our estimation, it is crucial to exclude the anticipated and ending effects. We implement more robust checks on baseline models, including eliminating the two years prior to the policy's implementation and the final year after the ETS pilot launch to avoid interference, shown in columns (1) and (2). Then, we narrow our sample to 2014–2017 to more closely observe the impact of carbon emission prices within the ETS period in column (3). Finally, a triple multiplicative term ETS × POST × t is included to offset the unobserved factor related to the time trend. The results of our study show that the existence of DID estimator is supported both economically and statistically, even at a significance level of 10%. Our findings, presented in **Table 6**, are robust and have undergone multiple checks, making them highly reliable for supporting our first hypothesis and forming the basis for further extrapolation.

Table 5

The PSM-DID and CS estimation results.

	(1)	(2)	(3)	(4)
Outcome variable	CO_2/Gen	CO_2/Gen	CO_2/Gen	CO_2/Gen
$ETS \times POST \times price$	-0.9487^{***}	-1.1073^{***}	-0.9725^{**}	-1.1901^{**}
	(0.1561)	(0.3828)	(0.4065)	(0.6019)
$ETS \times POST$	3.4494^{***}	4.4343^{***}	3.8105^{**}	4.5756^{*}
	(0.6848)	(1.6358)	(1.6156)	(2.461)
Control Variables	Yes	Yes	Yes	Yes
Provincial FE	Yes	Yes	Yes	Yes
Time FE	No	Yes	No	Yes
N	2158	2158	1269	1269
R^2	0.283	0.311	0.250	0.296

Notes: $p < 0.10$, $p < 0.05$, $p < 0.01$ are displayed with *, **, ***, respectively. FE is the abbreviation for "Fixed effect.". Standard errors are clustered at provincial level for all regressions. PSM technique is applied to columns (1) and (2). For each treated power plant, 2 control plants with similar estimated infiltration likelihood based on observed characteristics are selected and we set a caliper threshold of ±0.05 for the difference in propensity scores between treatment and control groups. Columns (3) and (4) use the CS's estimator.

Table 6

More robust checks on baseline results.

	(1)	(2)	(3)	(4)
Outcome variable	CO_2/Gen	CO_2/Gen	CO_2/Gen	CO_2/Gen
	Exclude anticipated effect	Exclude ending effect	Narrow sample window	Exclude time trend
$ETS \times POST \times price$	-1.0246^{***}	-1.0860^{***}	-3.0617^{***}	-1.0584^{**}
	(0.3624)	(0.3546)	(0.6338)	(0.4627)
$ETS \times POST$	3.7551^{***}	4.3008^{***}	10.8998^{***}	4.4268
	(1.3046)	(1.4565)	(2.6064)	(3.4149)
$ETS \times POST \times t$				-0.0519
				(0.2258)
Control Variables	Yes	Yes	Yes	Yes
Time FE	Yes	Yes	Yes	Yes
Provincial FE	Yes	Yes	Yes	Yes
N	1021	1184	422	1269
R^2	0.303	0.317	0.368	0.301

Notes: $p < 0.10$, $p < 0.05$, $p < 0.01$ are displayed with *, **, ***, respectively. FE is the abbreviation for "Fixed effect.". Standard errors are clustered at provincial level for all regressions.

4.3. Heterogeneity analysis

We delve deeper into grouped regressions and present the results in **Tables 7 and 8**. We divided the total into two parts: eastern and midland & western. The standard was compiled from official documents from China's National Bureau of Statistics. Our findings show that the absolute value of the estimator in the midland and western group is 2.5 times higher than in the eastern group, indicating that the impact of carbon prices on reducing emissions is more effective in less-developed regions. Although counterintuitive, this result is inspired by the idea that newcomers lead the way. The outdated technologies and equipment of coal-fired plants in western China offer more potential for adopting clean technologies and transitioning their energy portfolio, when faced with the same carbon price and MAC curve.

We assess the varying impact of power plant attributes, as shown in **Tabl**e **8**. We start by building a risk index in TransitionZero (2021) to evaluate power plant vulnerability, considering factors such as age, size, undepreciated value, and replacement cost. We categorize the plants into two groups: low risk and high risk, based on the mean. The results in columns (1) and (2) suggest that the effect of a carbon price on emissions is more pronounced in low-risk plants, likely due to their greater resilience and sustainability. Next, we compare power plant efficiency by dividing it by gross lower heating value in columns (3) and (4). Our findings reveal that low-efficiency plants are more vulnerable to strict carbon prices, which is consistent with Cui et al. (2019). Additionally, the impact of carbon prices is only significant in plants with high operational costs, as shown in columns (5) and (6). Based on these results, we conclude that the effect of carbon prices will likely be most effective for a specific region or group, particularly older plants with low efficiency and high costs of operation.

Table 7

The heterogeneous effect of plants' location area.

	(1)	(2)	(3)	(4)
Outcome variable	CO_2/Gen	CO_2/Gen	CO_2/Gen	CO_2/Gen
	Eastern	Midland & Western	Eastern	Midland & Western
$ETS \times POST \times price$	-0.9725**	-2.8106***	-1.1901*	-2.5271***
	(0.4065)	(0.4834)	(0.6019)	(0.3488)
$ETS \times POST$	3.8105**	9.0435***	4.5756	8.3229***
	(1.6156)	(1.5721)	(2.5065)	(1.1965)
Control Variables	Yes	Yes	Yes	Yes
Provincial FE	Yes	Yes	Yes	Yes
Time FE	Yes	Yes	Yes	Yes
N	428	821	428	821
R^2	0.289	0.347	0.383	0.373

Notes: $p < 0.10$, $p < 0.05$, $p < 0.01$ are displayed with *, **, ***, respectively. FE is the abbreviation for "Fixed effect.". Standard errors are clustered at provincial level for all regressions. The division standard for eastern, midland, and western are consistent with the official document from China's National Bureau of Statistics.

Table 8

The heterogeneous effect of plants' operational attributes.

	(1)	(2)	(3)	(4)	(5)	(6)
Outcome variable	CO_2/Gen	CO_2/Gen	CO_2/Gen	CO_2/Gen	CO_2/Gen	CO_2/Gen
Grouping Variable	Low risk	High risk	High efficiency	Low efficiency	High run costs	Low run costs
$ETS \times POST \times price$	-1.1338**	0.5819	-0.2941	-1.2776**	-4.1022**	-0.4992
	(0.4508)	(1.3405)	(0.1857)	(0.5084)	(1.5615)	(0.3412)
$ETS \times POST$	4.2334**	-1.3240	1.1856*	4.5657**	12.9316**	2.0088
	(1.6306)	(3.3605)	(0.5992)	(1.9352)	(4.9801)	(1.3398)
Control Variables	Yes	Yes	Yes	Yes	Yes	Yes
Provincial FE	Yes	Yes	Yes	Yes	Yes	Yes
Time FE	Yes	Yes	Yes	Yes	Yes	Yes
N	568	701	585	684	304	964
R^2	0.510	0.358	0.564	0.403	0.557	0.271

Notes: $p < 0.10$, $p < 0.05$, $p < 0.01$ are displayed with *, **, ***, respectively. FE is the abbreviation for "Fixed effect.". Standard errors are clustered at provincial level for all regressions. The indicator for high and low risks are on the basis of whether the overall risk index score above average, and columns (3) (4) are divided in line with the gross lower heating value (LHV) of coal-fired plants, while the last two are separated in line with the maintenance costs of coal-fired plants. All data stem from TransitionZero (2021).

4.4. How revenues change with carbon trading?

By analyzing the adjustments made by power plants to comply with the ETS regulation, we uncover the impact on four key operational attributes: run cost (SRMC and LRMC), and profitability (gross profitability and net profitability). **Table 9** presents our findings, which were obtained by applying the benchmark model outlined in **Equation (1)**.

Our findings reveal a substantial shift in the run cost and profitability of power plants due to fluctuations in carbon prices. A 1% increase in carbon price leads to a decrease of approximately 5.03 and 7.52 \$/MWh in SRMC and LRMC, representing 11.1% and 15.3% of their means, respectively. Despite this impact, gross profitability appears to be less affected than net profitability, indicating that the carbon price's effect on a power plant's assets and investment structure is more significant in the long term rather than in the short term.

The carbon emission price has a clear impact on power plants, not only reducing operational costs but also increasing profitability. This shift in input-output structure and innovation direction, as a result of the carbon price shock, was noted by Dong et al. (2022). Our findings address the concern that carbon regulation will create a competitive advantage for power plants exposed to fluctuating carbon prices. Our empirical results show that the second null hypothesis, that tighter carbon transaction prices can benefit plant profitability by reducing run costs, cannot be rejected.

Table 9

Estimation on revenues and run marginal cost of plants.

Outcome variable	(1) SRMC	(2) LRMC	(3) Gross profitability	(4) Net profitability
$ETS \times POST \times price$	-5.0315^{***}	-7.5155^{***}	1.2884^{*}	3.7724^{***}
	(1.6711)	(1.9500)	(0.7300)	(0.9447)
$ETS \times POST$	18.8282^{***}	27.1867^{***}	-3.9879	-12.3464^{***}
	(6.3315)	(7.6943)	(2.6465)	(4.0021)
Control Variables	Yes	Yes	Yes	Yes
Provincial FE	Yes	Yes	Yes	Yes
Time FE	Yes	Yes	Yes	Yes
N	1269	1269	1269	1269
R^2	0.564	0.505	0.938	0.896

Notes: $p < 0.10$, $p < 0.05$, $p < 0.01$ are displayed with *, **, ***, respectively. FE is the abbreviation for "Fixed effect.". Standard errors are clustered at provincial level for all regressions.

4.5. Channels on marginal abatement cost and accelerated depreciation

As the increases in carbon price, the rising MAC may prompt utilities to retire their older, high-emission power plants earlier than originally planned due to the increased cost of emissions. It is also achieved through accelerated depreciation, which enables the business to write off the value of the retired asset at a faster pace and so lower the business's taxable income. As illustrated in **Table 10**, columns (1) and (2) represent the outcomes of regressing carbon prices on MAC, while columns (3) and (4) represent the outcomes of interacting the original DID term with MAC using a modified version of the baseline model (4). According to estimates, a 1% increase in the price of carbon results in an increase of 5.42 \$/t CO2, or 19.7% of it, depending on the value adjusted levelized costs of power from either solar PV or onshore wind, from column (2). On the other hand, in columns (3) and (4), our most interesting term is negative substantially at least at the 10% level and conveys the ongoing reduction in emission intensity of power plants. This term results from the constrictions of MAC driven by the tightening carbon prices, which is the intramural mechanism. And with the aid of advancements in more transparent technology and apparatus, the increasing MAC can force the regulated power plants with excessive emissions to shoulder the obligations for abatement emissions (Ellerman and Decaux, 1998; Mo et al., 2021).

We next investigate the role of carbon intensity reduction through accelerated depreciation of old power plants. As shown in **Table 11**, the increases in carbon emission prices lead to a significant decline in the undepreciated valued of power plant, at least 1% statistical level in empirical models adding control variables or not, suggesting that the accelerated depreciation driven by the rising carbon prices can incentivize the retirement of high-emitting power plants, making it more economically attractive to deploy low-carbon alternatives, and thusly in turn lead to a averaged decrease in the carbon intensity of the power sector (Lehr, 2019).

The aforementioned result emphasizes the crucial role that the MAC and accelerated depreciation will play in providing incentives for power plants to reduce their emissions, which is in line with our third hypothesis.

Table 10

Channel estimation on MAC of plants.

	(1)	(2)	(3)	(4)
Outcome variable	MAC	MAC	CO_2/Gen	CO_2/Gen
$ETS \times POST \times price$	4.3421^{**}	5.4199^{***}		
	(1.6847)	(1.4428)		
MAC			-0.1831^{***}	
			(0.0401)	
$ETS \times POST \times price \times MAC$				-0.0062^{*}
				(0.0036)
Control Variables	Yes	Yes	Yes	Yes
Provincial FE	Yes	Yes	Yes	Yes
Time FE	Yes	Yes	Yes	Yes
N	1269	1269	1269	1269
R^2	0.703	0.715	0.589	0.295

Notes: $p < 0.10$, $p < 0.05$, $p < 0.01$ are displayed with *, **, ***, respectively. FE is the abbreviation for “Fixed effect.”. Standard errors are clustered at provincial level for all regressions.

Table 11

Channel estimation on accelerated depreciation of plants.

	(1)	(2)	(3)	(4)
Outcome variable	UDV	UDV	lnUDV	lnUDV
$ETS \times POST \times price$	-26205.87^{***}	-34449.72^{***}	-0.0591^{***}	-0.0733^{***}
	(5638.203)	(10778.97)	(0.0132)	(0.0222)
$ETS \times POST$	92484.91^{***}	123457.3^{***}	0.2160^{***}	0.2660^{***}
	(24142.72)	(35998.79)	(0.0605)	(0.0784)
Control Variables	No	Yes	No	Yes
Provincial FE	Yes	Yes	Yes	Yes
Time FE	Yes	Yes	Yes	Yes
N	1269	1269	1269	1269
R^2	0.703	0.715	0.589	0.295

Notes: $p < 0.10$, $p < 0.05$, $p < 0.01$ are displayed with *, **, ***, respectively. FE is the abbreviation for “Fixed effect.”.

Standard errors are clustered at provincial level for all regressions.

4.6. Powering the transition from coal to clean

China's transition to clean energy heavily relies on the utilization of its existing coal-fired power fleet. Nonetheless, due to the complex interests of stakeholders such as to create jobs, boost local economic growth, and allow for greater integration of renewables, China constructed more than one large coal-fired power plant each week last year. China aims to reach net-zero carbon emissions by 2060, a goal that requires shutting down, converting, or putting excess capacity into reserve (Kefford et al., 2018; Springer et al., 2022). We assess the feasibility of accelerating the transition of power plants to meet this target as carbon prices rise. The results, illustrated in **Table 12**, support the testimony that the stress carbon prices can accelerate these coal plants cleanly and effectively in the zero-net transitional path, strongly supporting our fourth hypothesis.

Explicitly arguing, the preferred estimate in column (2) in **Table 12** shows that a 1% increase in the carbon emission price can curtail about 0.01497 years for the expected net-zero retirement of power plants, and as 0.0007% of its mean (2033.98), which is the same as column (4). According to Cao et al. (2016), scenarios R2CUT and R2LUMP involve high carbon pricing with a rising rate and the introduction of subsidies for renewable power (i.e. hydro, nuclear, wind, and solar power) in the electricity sector to reach the levels specified by the IEA (2014). These subsidies are financed by a fossil fuel tax based on the carbon content of fuels and increase over time, as the share of renewable energy increases and the integration of renewable energy into the grid, so as to ensure a consistent, affordable and dependable supply of electricity. In R2CUT and R2LUMP scenarios, it is estimated that if the carbon price of China's ETS reaches 157 CNY per CO2ton and 149 CNY per CO2ton respectively, the mean retirement year of China's power plants can be further shortened by 0.0885% (157–30.64) × 0.0007) and 0.0829% (149–30.64) × 0.0007, respectively, resulting in 1.8001 and 1.6862 fewer years of retirement. This suggests that the average time for China to reach carbon peaking could be shortened to 2032.18 (2033.98–1.8001) and 2032.29 (2033.98–1.6862) under R2CUT and R2LUMP scenarios respectively. In general, the lifespan of power units will be greatly shortened by higher carbon emission prices, accelerating the transition to a net-zero emission economy.

Table 12

Estimation on net-zero retirement of plants.

	(1)	(2)	(3)	(4)
Outcome variable	Net-zero retirement time	Net-zero retirement time	Log of net-zero retirement time	Log of net-zero retirement time
$ETS \times POST \times price$	-1.5493^{***}	-1.4597^{**}	-0.0007^{***}	-0.0007^{**}
	(0.5391)	(0.6152)	(0.0003)	(0.0003)
$ETS \times POST$	5.7006^{*}	5.0062^{*}	0.0027^{*}	0.0025

	(3.0614)	(2.8746)	(0.0015)	(0.0014)
Control Variables	Yes	Yes	Yes	Yes
Time FE	Yes	Yes	Yes	Yes
Provincial FE	Yes	Yes	Yes	Yes
N	1269	1269	1269	1269
R^2	0.349	0.367	0.619	0.650

Notes: $p < 0.10$, $p < 0.05$, $p < 0.01$ are displayed with *, **, ***, respectively. FE is the abbreviation for "Fixed effect.". Standard errors are clustered at provincial level for all regressions.

5. Conclusion and policy implications

The electricity sector in China contributes to 44% of national carbon emissions, making it a crucial factor in the country's efforts towards carbon neutrality. This study uses China's eight regional ETS pilots as a quasi-natural experiment and applies a staggered DID method with a novel micro-level dataset of 1269 coal-fired power plants from 2009 to 2019 to examine the effect of local carbon prices on power plant emission intensity. We find the emission intensity will be reduced with the increases in carbon emission prices of ETS pilots, which is more profound for low-risk, low-efficiency but high-cost power plants, particularly those in China's midland and western regions. The improved efficiency will not be at the expense of output and profitability which is more significant in the long term rather than in the short term. Additionally, rising MAC and accelerated depreciation driven by climbing carbon prices may encourage utilities to retire high-emission power plants sooner than originally planned, leading to lower emissions intensity. Lastly, the average retirement years of China's power plants can be greatly shortened by rising carbon prices of ETS. Our findings indicate the substantial potentials for net-zero emission of China's electric power industry under the regulation of ETS and dynamic carbon prices, and several following policy implications can be drawn as follows:

Firstly, to promote the low-carbon transformation of the power sector, a long-term, steadily rising carbon price scheme should be formulated. This will internalize the external costs of carbon emissions through market-based mechanisms such as ETS. Our results demonstrate that higher carbon prices will lead to lower carbon emission intensity from coal-fired power plants. However, the reduction in emission intensity requires coal-fired power plants to gradually upgrade their power generation technologies. To create carbon price expectations and encourage technological progress, the technology benchmark in ETS should be increased and carbon quotas reduced. This will ensure that coal power plants are incentivized to adopt more efficient power generation technologies.

Secondly, it is essential to strengthen the institutional framework for the energy transition of the power sector. To this end, China should put in place a regulatory system to ensure the successful and efficient implementation of the ETS. The regulatory system should consist of a set of rules, regulations, and policies that govern the ETS and set clear policies and objectives to support the energy transition of the power sector.

Furthermore, an effective monitoring and enforcement mechanism should be established to ensure that the ETS is enforced in the power sector. Additionally, the development of renewable energy technology should be supported by various incentives, such as subsidies and tax credits. This will encourage the development of clean energy and promote the use of renewable energy in the power sector.

Thirdly, the government should lead more comprehensive research on the carbon markets and coal-fired power plants. Our study has made the first step and drew some conclusions that are different from the theoretical model in previous documents. To better protect the ecological and environmental, the government should increase the disclosure of more detailed data from related departments. Furthermore, China's government should expand the scope and scale of ETS, introducing more varieties of carbon financial products to enhance energy efficiency and emission intensity reduction. Moreover, more in-depth scenarios assessment on different carbon prices should be conducted to serve as a better policy basis.

There are some research limitations and further directions. Firstly, our empirical estimation typically relies on historical data to infer the relationship between variables, which may not account for future changes in technology or policy. For instance, achieving a net-zero retirement goal may require significant changes to the energy sector, including the adoption of renewable energy sources and energy efficiency measures, to ensure that the electricity supply remains both affordable and reliable. Therefore, to better analyze the long-term impacts of different policy scenarios and evaluate the trade-offs between different policy objectives, integrating assessment models (IAMs) can be used. These computational models simulate the interactions between different components of the economy and the environment. While IAMs may be oversimplification or misrepresentation of the real world, combining them with econometrics models may be the focus of our work in the next step to better inform policy formulation. Secondly, the data used in this paper is before 2019, prior to the implementation of a national unified carbon trading market in China. Therefore, to what extent the emission intensity of China's coal-fired power plants would shift with carbon prices after the implantation of a national unified carbon trading market is a pivotal question for future ETS experimentation and empirical research. Thirdly, this paper only applies to the Chinese context and further research is needed to examine the effects of carbon pricing on emission intensity in other developing countries especially in South and Southeast Asia.

CRediT authorship contribution statement

Qingyang Wu: Conceptualization, Formal analysis, Investigation, Methodology, Visualization, Supervision, Writing – original draft, Writing – review & editing. Chang Tan: Data curation, Conceptualization, Investigation, Writing – original draft. Daoping Wang: Data curation, Methodology, Visualization, Writing – original draft. Yongtao Wu: Data curation, Methodology, Formal analysis. Jing Meng: Methodology, Formal analysis, Interpretation, and, Writing – review & editing. Heran Zheng: Methodology, Formal analysis, Interpretation, and, Writing – review & editing.

Declaration of competing interest

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

Data availability

Data will be made available on request.

References

Biresselioglu, M. E., & Yelkenci, T. (2016). Scrutinizing the causality relationships between prices, production and consumption of fossil fuels: A panel data approach. Energy, 102, 44-53.

Brouwers, R., Schoubben, F., & Van Hulle, C. (2018). The influence of carbon cost pass through on the link between carbon emission and corporate financial performance in the context of the European Union Emission Trading Scheme. Business Strategy and the Environment, 27(8), 1422-1436.

Callaway, B., & Sant'Anna, P. H. (2021). Difference-in-differences with multiple time periods. *Journal of Econometrics*, *225*(2), 200-230.

Cao, J., Ho, M. S., & Timilsina, G. R. (2016). Impacts of carbon pricing in reducing the carbon intensity of China's GDP. World Bank Policy Research Working Paper, (7735).

Cao, J., Ho, M. S., Ma, R., & Teng, F. (2021). When carbon emission trading meets a regulated industry: Evidence from the electricity sector of China. Journal of Public Economics, 200, 104470.

Chen, R. (2021). Evaluating Power Sector Emissions under China's Regional Carbon ETS Pilots: A View from Space. Available at SSRN 3963306.

Chen, Z., Zhang, X., & Chen, F. (2021). Do carbon emission trading schemes stimulate green innovation in enterprises? Evidence from China. Technological Forecasting and Social Change, 168, 120744.

Chevallier, J. (2009). Carbon futures and macroeconomic risk factors: A view from the EU ETS. Energy Economics, 31(4), 614-625.

China's National Bureau of Statistics. (2022). Statistical bulletin on national economic and social development in the People's Republic of China. http://www.stats.gov.cn/tjsj/zxfb/202202/t20220227_1827960.html

Cui, J., Wang, C., Zhang, J., & Zheng, Y. (2021). The effectiveness of China's regional carbon market pilots in reducing firm emissions. Proceedings of the National Academy of Sciences, 118(52).

Cui, R. Y., Hultman, N., Edwards, M. R., He, L., Sen, A., Surana, K., ... & Shearer, C. (2019). Quantifying operational lifetimes for coal power plants under the Paris goals. Nature communications, 10(1), 1-9.

Dong, H., Liu, W., Liu, Y., & Xiong, Z. (2022). Fixed asset changes with carbon regulation: The cases of China. Journal of Environmental Management, 306, 114494.

Ellerman, A. D., & Decaux, A. (1998). Analysis of post-Kyoto CO_2 emissions trading using marginal abatement curves.

Frondel, M., & Schubert, S. A. (2021). Carbon pricing in Germany's road transport and housing sector: Options for reimbursing carbon revenues. Energy Policy, 157, 112471.

Gao, D., Li, Y., & Li, G. (2022). Boosting the green total factor energy efficiency in urban China: Does low-carbon city policy matter?. Environmental Science and Pollution Research, 1-16.

Goh, T., Ang, B. W., Su, B., & Wang, H. (2018). Drivers of stagnating global carbon intensity of electricity and the way forward. Energy Policy, 113, 149–156. https://doi.org/10.1016/j.enpol.2017.10.058

Harris, N., & Gibbs, D. (2021, January 21). Forests absorb twice as much carbon as they emit each year. World Resources Institute. Retrieved April 2, 2022, from https://www.wri.org/insights/forests-absorb-twice-much-carbon-they-emit-each-year

Hu, Y., Ren, S., Wang, Y., & Chen, X. (2020). Can carbon emission trading scheme achieve energy conservation and emission reduction? Evidence from the industrial sector in China. Energy Economics, 85, 104590.

IEA (2014), World Energy Outlook 2014, IEA, Paris.

IEA, 2020. China’s Emissions Trading Scheme. IEA, Paris. https://www.iea.org/reports/chinas-emissions-trading-scheme.

IEA, 2021. Net zero by 2050: a roadmap for the global energy sector. https://www.iea.org/reports/net-zero-by-2050.

IEA, 2022a. Global CO2 Emissions Rebounded to Their Highest Level in History in 2021. https://www.iea.org/news/global-co2-emissions-rebounded-to-their-highest-level-in-history-in-2021.

IEA, 2022b. Electricity emissions factors 2021. https://www.iea.org/data-and-statistics/data-product/emissions-factors-2021.

Jiang, H. D., Purohit, P., Liang, Q. M., Dong, K., & Liu, L. J. (2022). The cost-benefit comparisons of China's and India's NDCs based on carbon marginal abatement cost curves. Energy Economics, 105946.

Jin, B., & Han, Y. (2021). Influencing factors and decoupling analysis of carbon emissions in China’s manufacturing industry. Environmental Science and Pollution Research, 28(45), 64719-64738.

Kefford, B. M., Ballinger, B., Schmeda-Lopez, D. R., Greig, C., & Smart, S. (2018). The early retirement challenge for fossil fuel power plants in deep decarbonisation scenarios. Energy policy, 119, 294-306.

Kim, P., & Bae, H. (2022). Do firms respond differently to the carbon pricing by industrial sector? How and why? A comparison between manufacturing and electricity generation sectors using firm-level panel data in Korea. Energy Policy, 162, 112773.

Koch, N. (2014). Dynamic linkages among carbon, energy and financial markets: a smooth transition approach. Applied Economics, 46(7), 715-729.

Lehr, R. (2019, May 15). *How arcane accounting rules could help save coal-heavy utilities*. Utility Dive. https://www.utilitydive.com/news/how-arcane-accounting-rules-could-help-save-coal-heavy-utilities/554773/

Leitao, J., Ferreira, J., & Santibanez-Gonzalez, E. (2021). Green bonds, sustainable development and environmental policy in the European Union carbon market. Business Strategy and the Environment, 30(4), 2077-2090.

Liu, J. Y., Woodward, R. T., & Zhang, Y. J. (2021). Has carbon emissions trading reduced PM2. 5 in China?. Environmental Science & Technology, 55(10), 6631-6643.

Liu, Q., Zheng, X.-Q., Zhao, X.-C., Chen, Y., & Lugovoy, O. (2018). Carbon emission scenarios of China's power sector: Impact of controlling measures and carbon pricing mechanism. Advances in Climate Change Research, 9(1), 27–33. https://doi.org/10.1016/j.accre.2018.01.002

Luo, Y., Li, X., Qi, X., & Zhao, D. (2021). The impact of emission trading schemes on firm competitiveness: Evidence of the mediating effects of firm behaviors from the guangdong ETS. Journal of Environmental Management, 290, 112633.

Mo, J., Zhang, W., Tu, Q., Yuan, J., Duan, H., Fan, Y., ... & Meng, Z. (2021). The role of national carbon pricing in phasing out China's coal power. IScience, 24(6), 102655.

Mu, Y., Wang, C., & Cai, W. (2018). The economic impact of China's INDC: Distinguishing the roles of the renewable energy quota and the carbon market. Renewable and Sustainable Energy Reviews, 81, 2955-2966.

Nhuchhen, D. R., Sit, S. P., & Layzell, D. B. (2022). Towards net-zero emission cement and power production using Molten Carbonate Fuel Cells. Applied Energy, 306, 118001.

Person, & Stanway, D. (2022, February 24). China starts building 33 GW of coal power in 2021, most since 2016 -research. Reuters. Retrieved April 9, 2022, from https://www.reuters.com/markets/commodities/china-starts-building-33-gw-coal-power-2021-most-since-2016-research-2022-02-24/

Qi, S., Cheng, S., & Cui, J. (2021). Environmental and economic effects of China's carbon market pilots: Empirical evidence based on a DID model. Journal of Cleaner Production, 279, 123720.

Shan, Y., Huang, Q., Guan, D., & Hubacek, K. (2020). China CO2 emission accounts 2016-2017. Scientific Data, 7(1), 1–9. https://doi.org/10.1038/s41597-020-0393-y

Springer, C., Shi, D., & Kudrimoti, A. (2022). 7 The political economy of coal. The Political Economy of Coal: Obstacles to Clean Energy Transitions.

Tan, X., Sun, Q., Wang, M., Cheong, T. S., Shum, W. Y., & Huang, J. (2022). Assessing the effects of emissions trading systems on energy consumption and energy mix. Applied Energy, 310, 118583.

Tong, D., Zhang, Q., Zheng, Y., Caldeira, K., Shearer, C., Hong, C., Qin, Y., & Davis, S. J. (2019). Committed emissions from existing energy infrastructure jeopardize 1.5 °C climate target. Nature, 572(7769), 373–377. https://doi.org/10.1038/s41586-019-1364-3

TransitionZero (2021). Turning the supertanker. Retrieved April 1, 2022, from https://www.transitionzero.org/thank-you-report-turning-the-supertanker

Waheed, R., Sarwar, S., & Wei, C. (2019). The survey of economic growth, energy consumption and carbon emission. Energy Reports, 5, 1103-1115.

Wang, C., Wang, Z., Ke, R. Y., & Wang, J. (2018). Integrated impact of the carbon quota constraints on enterprises within supply chain: Direct cost and indirect cost. Renewable and Sustainable Energy Reviews, 92, 774-783.

Wang, J., & Li, H. (2019). The mystery of local fiscal expenditure and carbon emission growth in China. Environmental Science and Pollution Research, 26(12), 12335-12345.

Wang, Q., & Wang, L. (2021). The nonlinear effects of population aging, industrial structure, and urbanization on carbon emissions: a panel threshold regression analysis of 137 countries.

Journal of Cleaner Production, 287, 125381.

Wang, Q., Li, B., Chen, B., Cheng, Y., & Wang, Z. (2021). Implication of take-back and carbon emission capacity regulations on remanufacturing in a competitive market. Journal of Cleaner Production, 325, 129231.

Wu, Q. (2022). Price and scale effects of China's carbon emission trading system pilots on emission reduction. *Journal of Environmental Management*, *314*, 115054.

Wu, Q., & Wang, Y. (2022). How does carbon emission price stimulate enterprises' total factor productivity? Insights from China's emission trading scheme pilots. *Energy Economics*, 105990.

Xue, Z., Li, N., Mu, H., Zhang, M., & Pang, J. (2021). Convergence analysis of regional marginal abatement cost of carbon dioxide in China based on spatial panel data models. Environmental Science and Pollution Research, 28(29), 38929-38946.

Yang, Z., Yuan, Y., & Zhang, Q. (2022). Carbon Emission Trading Scheme, Carbon Emissions Reduction and Spatial Spillover Effects: Quasi-Experimental Evidence From China. Frontiers in Environmental Science, 684.

Yu, P., Hao, R., Cai, Z., Sun, Y., & Zhang, X. (2022). Does emission trading system achieve the win-win of carbon emission reduction and financial performance improvement? — Evidence from Chinese A-share listed firms in industrial sector. Journal of Cleaner Production, 333, 130121.

Zhao, Y., Li, H., Xiao, Y., Liu, Y., Cao, Y., Zhang, Z., Wang, S., Zhang, Y., & Ahmad, A. (2018). Scenario analysis of the carbon pricing policy in China’s power sector through 2050: Based on an improved CGE model. Ecological Indicators, 85, 352–366. https://doi.org/10.1016/j.ecolind.2017.10.028

Zhu, J., Ge, Z., Wang, J., Li, X., & Wang, C. (2022). Evaluating regional carbon emissions trading in China: effects, pathways, co-benefits, spillovers, and prospects. Climate Policy, 1-17.