

From grey to green: The role of emission trading schemes in China's urban transformation

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ABSTRACT

This study explores the impact of China's pilot Emission Trading Schemes (ETS) on Urban Green Development Efficiency (UGDE). We compare the established crediting baselines of ETSs in six carbon markets from 2003 to 2020 with counterfactuals derived post-hoc using a quasi-experimental synthetic control method over the same period. Key findings include: First, the results strongly suggest that the ETS significantly enhance UGDE. The aggregate results show that in pilot regions, the ETS enhances UGDE by approximately 10%–15% compared to synthetic regions. Second, the extent of UGDE improvement due to the ETS varies significantly across regions. The UGDE improvements in these pilot ETS markets, listed in descending order of effectiveness, are Tianjin, Hubei, Shanghai, Chongqing, and Guangdong. Third, robustness tests such as the counterfactual and placebo tests confirm that ETS improves UGDE. Fourth, we identified two key mechanisms through which ETS boosts green comprehensive efficiency: technological innovation and industry restructuring. Overall, this study provides concrete policy insights for refining ETS design and for enhancing green development policies.

1. Background

Since 2007, China has been the world's largest producer of anthropogenic greenhouse gases (GHGs) (IEA, 2009; Jiang et al., 2010). China faces escalating pressure to curb the growth of its energy consumption and GHG emissions. Considering the significant benefits of market-based instruments, including cost efficiency, flexibility, predictability, and transparency, China's climate policy has recently moved away from traditional command-and-control approaches (Stavins, 2003; [1,2]). A flagship climate policy initiative, the pilot carbon emission trading scheme (ETS), was launched in 2011 [3]. Following the official launch of the long-awaited national ETS on June 25, 2021, the Chinese government is committed to enhancing carbon emission reductions through market-based strategies. Despite its significance, the ecological and socioeconomic impacts of ETS, along with their policy transmission mechanisms, remain understudied [4].

To fulfil its aim of reducing carbon emissions at the lowest overall social cost, ETS takes advantage of the market mechanism's crucial role in dispersing carbon emission resources [5]. Businesses can trade surplus carbon emissions within the ETS, guided by carbon pricing and caps, which naturally regulate their behavior. Reasonable cap setting and quota allocation serve as safeguards for emission control, determining whether a carbon market operates under a cap-and-trade system or an intensity system. In cap-and-trade systems, predetermined absolute emission ceilings are applied regardless of enterprises' actual activities during compliance periods, enabling direct control over overall emissions. Two primary free quota allocation methods are employed: the grandfathering method and the benchmarking method. The grandfathering approach requires predetermined total quotas, including historical emissions and historical emission intensity. However, due to uncertainties in economic development projections, carbon emission growth forecasts, energy price fluctuations, and emission reduction

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technology innovations, emission caps may deviate from actual conditions [6]. The hallmark of intensity-based carbon markets is that allocated quotas are not predetermined but determined by enterprises' industry-specific carbon performance benchmarks and operational activities during compliance periods. Companies can adjust production strategies to secure quotas, incentivizing emission reductions and capacity optimization through emission intensity management. Intensity benchmark systems can also give incentives to operate more efficient coal-power plants over less efficient ones. China has been actively exploring climate policies tailored to its national context, particularly debating whether to adopt an intensity-based or absolute-quantity target carbon trading framework [6]. The initial carbon emission trading pilots approved in November 2011 covered six provincial-level regions (Chongqing, Guangdong, Hubei, Beijing, Tianjin, and Shanghai) and one prefecture-level region (Shenzhen). It is important to note that these pilot ETSs each had unique market designs and operated independently [7]. As ETS is a top priority for policymakers, it is recognized as an effective tool for reducing GHG emissions. However, the real socioeconomic impacts of these seven pilot ETSs require thorough investigation [8].

Due to varying levels of economic development, energy consumption patterns, and structural adjustments in key industries across regions, ETS programs have been independently designed and implemented with distinct characteristics [9]. Pilot projects exhibit significant differences in ETS quota allocation methods and industry coverage (shown in Table 1). Treating all pilot regions as homogeneous subjects may lead to biased analytical results, thus requiring thorough consideration of regional heterogeneity. Notably, Beijing and Shanghai demonstrate unique sampling characteristics. Beijing, as China's capital, plays a crucial role in disseminating government policies. Enterprises in Beijing have closely monitored these policies, adjusting their production and carbon trading strategies accordingly [10]. Changes in industrial structure and technological inputs in Beijing have led to significantly higher green development efficiency compared to other regions [11]. Additionally, as an international metropolis and financial hub, Shanghai has pioneered numerous policy reforms, such as the Shanghai Municipal Carbon Emission Management Pilot Measures, and established frameworks like the Shanghai Environment and Energy Exchange Carbon Emission Trading Rules, alongside various pilot policies in carbon trading and finance. Consequently, Shanghai's comprehensive efficiency generally surpasses that of other regions [12]. In order to ensure that the subjects have a stronger comparability in core characteristics, this study will consider Beijing and Shanghai as two pilot areas separately in the subsequent pilot overall analysis.

There are two primary methods for meeting the ETSs' carbon reduction requirements. The ETS has potentially accelerated the shift towards cleaner energy sources more rapidly than traditional command-based policies [13]. However, this mechanism's potential may be limited by China's reliance on coal [13]. Conversely, enhancing energy efficiency could help reduce GHG emissions (Li and Colombier, 2009; [14]). ETSs are globally acknowledged as effective in reducing carbon emissions [8]. However, there are concerns among policymakers regarding the performance of established experimental ETSs. This approach stems from China's pilot reform, metaphorically described as 'throwing stones to ask the way'.

This study enhances the effectiveness evaluation framework for ETSs, providing quantifiable references for policy tools designed to mitigate GHG and promote urban green development. Specifically, this study utilizes China's pilot ETSs as a quasi-natural experiment, employing the Synthetic Control Model (SCM) to assess the impact on total factor productivity (TFP) across six pilot provinces: Chongqing, Guangdong, Hubei, Beijing, Tianjin, and Shanghai. Notably, Shenzhen, the pilot city located within Guangdong Province, will not be discussed separately here. Data envelopment analysis (DEA) is applied to measure TFP, providing an objective metric for UGDE assessment. Subsequently, this research explores the variability in policy impacts across different

Table 1
Key mechanism differences in China's provincial-level pilot ETSs.

Region	Sectoral coverage	Allowance allocation methods		
		Historical emission method	Historical intensity method	Benchmarking method
Tianjin	Ferrous metal, chemical materials, electricity power, oil processing, petroleum mining	All covered sectors excluding the electricity power	Electricity power	×
Shanghai	Ferrous metal, oil processing, chemical materials, non-ferrous metal, electricity power, non-metal, textile, papermaking, rubber, chemical fiber	All covered sectors excluding the electricity power	×	Electricity power
Chongqing	Non-metal, ferrous metal, electricity power, non-ferrous metal, chemical materials	Voluntary application		
Guangdong	Non-metal, ferrous metal, electricity power, oil processing	Oil processing	×	Non-metal, ferrous metal, electricity power
Beijing	Electricity power, non-metal, oil processing, ferrous metal	All covered sectors excluding the electricity power	Electricity power	×
Hubei	Ferrous metal, chemical materials, non-metal, transportation, electricity power, non-ferrous metal, papermaking	All covered sectors excluding the electricity power	×	Electricity power

cities and the mechanisms through which ETS affects UGDE. Ultimately, this research conducts a comprehensive and standardized robustness analysis, including placebo tests and mechanism evaluations.

This study makes three main contributions: First, while extensive research has been conducted on the impact of ETS on carbon emission reduction and environmental policies such as low-carbon city pilot programs on urban green development efficiency [15–17], there remains a scarcity of literature evaluating the Chinese pilot ETS's impact on the comprehensive evaluating indicator UGDE. Consequently, this study enriches the literature by first establishing and elucidating the diverse effects of ETS on UGDE. Secondly, while prior literature often treats pilot regions as a homogeneous group, this study employs the Synthetic Control Method (SCM) to evaluate each pilot individual. It not only identifies the performance ranking across different regions (e.g., the superior performance of Tianjin and Hubei) but also delves into how regional resource endowments and industrial structures lead to asymmetric policy effects, providing precise empirical evidence for differentiated governance in the national carbon market. Thirdly, building upon the "Porter Hypothesis," this paper further scrutinizes the mediating roles of technological innovation and industrial restructuring in enhancing green efficiency. Specifically, by incorporating the administrative context of China's power and heating sectors, the study explores

the time lags and structural constraints in policy transmission, thereby deepening the theoretical understanding of the relationship between environmental regulation and economic growth in the context of a transitioning economy.

2. Literature review and theoretical hypotheses

Theoretical frameworks suggest that strict and reasonable environmental regulations can internalize external costs and promote green technological innovation in enterprises ([18]; Lanoie et al., 2008; [19]). Extensive research exists on green development efficiency, particularly concerning the development of cities or regions and the benefits derived from various environmental policies (Marketta et al., 2020; [20–24]; Naeema & McShane, 2018). For instance, Li [12] developed an evaluation model combining weighted approaches and TOPSIS to assess Shanxi's green development efficiency from economic, environmental, societal, and energy perspectives. Liu et al. [25] used the slack-based measure model to analyze green development efficiency in Gansu's major cities from input and output perspectives. Yao and Zeng [4] assessed the ETS's effectiveness and explored if carbon trading achieved Pareto efficiency in reducing emissions costs and benefits. Total Factor Productivity (TFP) serves as a crucial measure of a region's green and high-quality development, reflecting resource allocation efficiency [26, 27].

2.1. Relationship between environmental policy and efficiency

Pollution detrimentally impacts both the economy and society. Societal costs of environmental degradation can be transformed into private costs for regulation. Market-based environmental regulations incur operating costs but significantly incentivize technological innovation in enterprises, thereby enhancing efficiency [28]. Marketable pollution permits, a form of carbon emission trading, allow enterprises to legally discharge pollutants through emission permits. Consequently, under such systems, environmental resources are treated as purchasable commodities ([29]; [70]).

Research into the efficiency impacts of the two trading systems covers diverse topics such as energy utilization, technological innovation, and industrial structure. There is no consensus on their specific impacts [30–34]. Lu [35] analyzed the data post-adoption of a low-carbon pilot strategy and found no discernible change in carbon emissions between the pilot groups. According to Schleich et al. [36], the advantages of the European Union (EU)ETS are limited to enhancing the present energy efficiency, although the situation may improve in the future. Shi and Lin [37] found that marketable pollution permits could significantly reduce energy consumption per GDP unit and enhance green total factor efficiency in prefecture-level cities. Li et al. [38] argued that pollution levies foster green innovation via external pressures and internal incentives, while environmental subsidies also promote it. Different environmental regulation tools yield varied effects. Tan et al. [1] observed that the ETS significantly 'forced' industrial structure upgrades in pilot areas, with regional variations. Stein (2010) posits that certain conditions must be met for marketable pollution permits to succeed. Policy objectives must be continuously and stably set, considering taxation, trading, supervision, and short-term strategies. Consequently, the effects of policy benefits and the internal mechanisms of environmental regulation on energy efficiency warrant further exploration.

Ren et al. (2019) applied the difference-in-differences (DID) method to assess the impact of the pilot sulfur dioxide (SO₂) emission trading system (ETS) on enterprises' TFP. This study inspired our work from a research viewpoint. Our study focuses on the 2011 ETS pilot policy. Although CO₂ and SO₂ emission trading are based on similar principles, in China, SO₂ trading is predominantly a government-controlled primary market, while CO₂ trading has evolved into a nearly perfect secondary market among firms [27]. At the end of 2015, China's then

Ministry of Environmental Protection conducted a comprehensive study on the experimental SO₂ ETSs. The study found that firms were insufficiently engaged in the SO₂ ETS [27]. Since the launch of the CO₂ ETS, traded carbon emissions have increased from 15.8 Mt in 2014 to 43.4 Mt in 2020. Given the considerable differences between the two policies, the SO₂ research may not yield clear insights into CO₂; therefore, the impact of ETS on TFP warrants specific investigation [27].

Although existing studies have explored the impact of China's ETS pilot programs on green development, they have certain limitations in terms of research objectives and indicator selection. The research objective of Liu et al. [39] was similar to that of this paper focusing on evaluating the emission reduction effect of ETS pilot projects. They adopted the SCM and combined it with the DID method for robustness tests. However, this study only focused on a single indicator of carbon dioxide emissions and failed to provide an assessment of the comprehensive green development efficiency at the urban level. Feng et al. [40] is the first empirical study on the impact of ETS in China on green total factor productivity (GTFP). They employed basic DID, PSM-DID and SDID to analyze the direct and indirect impacts of ETS on GTFP at the national, regional and urban levels. Their study enriches the literature because the GTFP indicator it adopts contains more information than carbon intensity or emission reduction and also provides a reference for the selection of indicators in this paper. However, its research perspective is different from the UGDE that this paper focuses on. Therefore, this paper is dedicated to evaluating the impact of China's ETS pilot programs on sustainable development at the urban level more scientifically and comprehensively by adopting comprehensive urban Green Development Efficiency indicators to fill the research gap.

2.2. ETS and enterprise business indicators

Business indicators are defined as metrics that reflect an enterprise's operating conditions, profitability, debt repayment capacity, and liquidity. Trading within the ETS operates on a quota system. For participants like countries, enterprises, or organizations with emission reduction targets, the ETS facilitates flexible, market-oriented trading to achieve cost-effective transactions [41,42].

Business indicators are an emerging concept, and the definition is expanded under the background of carbon trading policy. Based on an investigation into the liquidity of the ETS, Yao and Zeng [4] recommended tightening total carbon data, diversifying market participants, lowering market inclusion thresholds, and expanding market capacity. These proposals imply that the carbon usage by emission-control enterprises impacts the market's trading scope. R&D expenditure and patent applications serve as alternative indicators of enterprise technological innovation. Hu et al. [43] used these indicators to examine if the carbon emissions trading system enhances enterprise technological innovation. Rodriguez et al. [44] analyzed the intensity and efficiency of energy policies and argued that energy intensity indicators are misleading. Carbon trading policies incentivize reductions in corporate emissions, enabling enterprises to enhance production efficiency through technological innovation and meet emission control and reduction goals [18]. Consequently, the benefit evaluation system broadens the range of indicators measuring technical innovation.

2.3. Environmental policy evaluation method

The fundamental principle of policy evaluation is to explore performance differences under consistent external conditions, comparing scenarios with and without the policy implementation. Therefore, the key to evaluating the result depends on the identification of a perfect counterfactual control group [45]. Various policy evaluation methods, including the difference-in-differences (DID), breakpoint regression, and synthetic control methods, are employed to form counterfactual groups.

Hu et al. [43] demonstrated the DID model's effectiveness, showing that the carbon emissions trading mechanism significantly boosts

technological innovation in enterprises engaged in emission reduction, although ETS liquidity can limit these benefits. Gao et al. [46] used the DID model to investigate the emission reduction effects of ETS pilot cities. The ETS significantly reduced carbon emissions in Beijing, Shanghai, and Hubei, enhanced them in Guangdong, and had no significant effect in Tianjin. However, the ETS implemented in Guangdong had a significant promotion effect and that in Tianjin had no significant effect. Yan et al. [47] examine how China's ETS pilots not only reduce air pollution but also foster collaborative governance across government and market actors, thereby enhancing environmental regulatory effectiveness. Using the DID method, Shi and Lin [37] estimated how marketable pollution permits affect energy efficiency. They suggested that marketable pollution permits enhance government-market relations, increase marketization, reduce energy consumption per GDP unit, and boost green total factor energy efficiency. Qi et al. [48] explored if China's ETS policy reduced carbon emissions without hampering economic development, utilizing the DID model to compare pre- and post-implementation differences. The findings revealed that the ETS policy significantly lowered carbon emissions in ETS areas compared to non-ETS areas without impeding economic development. Li et al. [49] evaluated the synergistic benefits of ETS pilot policies in energy conservation and emission reduction, mainly using DID and PSM-DID methods. Their research found that there was regional heterogeneity in the policy effect (East China and Central China benefited, while the Western region did not). However, the method PSM-DID has methodological limitations such as sample size limitation, ignoring unobserved variables, and ignoring regional heterogeneity when applied to the pilot study of ETS in China [39]. Li [50] used the synthetic control method to find that power consumption intensity decreased in 2012's second-batch low-carbon pilot cities. The study showed heterogeneity among different types of cities, with provincial capitals experiencing only moderate population reductions. The SCM is widely used; for example, Billmeier and Nannicini [51] assessed the impact of economic liberalization policies, while Kim and Kim [52] evaluated the green gas initiative in the northeast United States.

When the DID method is used to evaluate the ETS construction policy, finding a control group with common trends and characteristics to the pilot cities is difficult. Significant differences across sample cities can lead to biases in estimating policy effects. Furthermore, pilot cities for ETS construction are chosen based on assessments of numerous factors by relevant departments, not at random. Consequently, these systematic differences introduce endogenous challenges, potentially biasing evaluation outcomes. The regression discontinuity design (RDD) method is suitable for uniform policy applications. Initially launched in seven pilot cities, the carbon trading market was subsequently refined and expanded. The samples close to the critical point must essentially be undifferentiated at the level of the control variables to use the regression discontinuity design method; otherwise, the estimation of the policy effect becomes biased [51].

2.4. Theoretical analysis and research hypotheses

From an economic perspective, the social costs associated with environmental degradation can be internalized as private production costs for enterprises through environmental regulation. As a market-based regulatory tool, the core logic of the Emission Trading Scheme (ETS) lies in defining scarce environmental capacity as a tradable commodity. Under this framework, the government sets an emissions cap and allocates permits, thereby assigning a clear price attribute to carbon emission rights.

For pilot cities, the ETS creates a flexible incentive-and-constraint mechanism. When a firm's actual emissions exceed its allocated quotas, it must purchase additional permits from the market, directly increasing its marginal production costs. Conversely, if a firm generates surplus quotas through efficiency improvements, it can profit by selling them. This price signal guides the optimal allocation of production

factors—such as capital, labor, and energy—across different firms and industries. Through this market-based screening mechanism, resources spontaneously flow toward production units with lower energy consumption and higher output. At the macro level, this enhances the overall Urban Green Development Efficiency (UGDE), achieving a significant reduction in undesirable outputs while maintaining economic growth. Accordingly, this study proposes hypotheses 1.

H1. The implementation of China's Emission Trading Scheme (ETS) significantly enhances Urban Green Development Efficiency (UGDE)

Contrary to increasing costs, strict environmental protection policies, such as ETS, may foster technological innovation, empowering manufacturers with a competitive edge and supporting their development [38]. Carbon trading regulates market behavior through a pricing mechanism. When reducing emissions becomes profitable, companies are motivated to invest in energy-saving and low-carbon technologies. Consequently, the ETS serves as a logical driver of technological innovation, which in turn plays a crucial role in enhancing comprehensive green efficiency in the region [43]. Therefore, examining the proportion of science and technology expenditure in regional fiscal revenue effectively indicates whether Porter's hypothesis applies during the implementation of green development policies driven by technological innovation. Based on this, we propose Hypothesis 2.

H2. Technological innovation serves as a key mechanism through which the ETS boosts UGDE.

A key objective of the ETS policy is to enhance the industrial structure in pilot areas, aiding in achieving peak carbon emissions by 2030 and carbon neutrality by 2060. The structure of the tertiary industry is optimized to increase the share of producer services, thereby raising the overall sector's contribution. Under the ETS, enterprises are incentivized to adopt low-carbon manufacturing methods, fostering technical innovation and market transformation. Technological innovation plays a crucial role in the optimization and upgrading of industrial structures [53]. Above all, we propose Hypothesis 3.

H3. Industrial structure optimization is another primary pathway for the ETS to influence UGDE.

Consequently, this study adopts the Synthetic Control Method (SCM) as its identification strategy. SCM addresses the absence of a comparable reference group. Each sample area's weight is determined numerically to form a weighted counterfactual control group, closely mirroring the characteristics and development trends of the pilot cities. This approach minimizes subjective selection and policy endogeneity.

3. Data and model

3.1. Data sources

To establish ex-ante similarity between the pilot areas before ETS trading and the synthetic control group, we selected various factors as explanatory variables. These include comprehensive green efficiency, GDP, economic growth rate, the proportion of the secondary industry, urbanization level, the proportion of fixed assets, investment in science and technology, environmental protection expenditure, energy structure, foreign direct investment (FDI), the number of authorized patents, and the number of college students per 100,000 people. All data were sourced from the Urban Statistical Yearbook of China covering the years 2003–2020.

The descriptive statistics in Table 2 reveal that the mean comprehensive efficiency is 1.043 with a standard deviation of 0.163, where the significant gap between the minimum (0.589) and maximum (1.326) suggests substantial regional imbalances in green development performance, justifying the use of the Synthetic Control Method (SCM) to identify comparable counterfactuals. The average economic growth rate of 10.259 % reflects the rapid growth phase of Chinese cities during the

Table 2
Descriptive statistics of variables.

Variable	Obs	Mean	Std	Min	Max
Comprehensive efficiency	540	1.043	0.163	0.589	1.326
GDP(Ln)	537	6.369	1.197	3.839	10.086
Economic growth rate	540	10.259	4.605	-25.016	29.879
Proportion of the secondary industry	540	45.133	8.608	15.800	62.000
Urbanisation level	540	53.563	14.558	24.770	89.600
Proportion of fixed assets	540	0.582	0.271	0.028	1.480
Proportion of science and technology investment	537	0.267	0.252	0.015	1.431
Proportion of environmental-protection expenditure	417	0.586	0.514	0.033	3.614
Energy structure	540	0.622	0.292	0.047	1.530
FDI foreign investment amount	537	2.468	2.297	0.005	10.602
Number of patents authorised (Ln)	540	9.152	1.638	4.248	12.715
Number of college students per 100000 people(Ln)	510	8.101	2.694	0.703	24.922

study period, yet the high standard deviation of GDP Ln (1.197) highlights a persistent chasm in regional economic scales. A mean secondary industry proportion of 45.133 % and an average energy structure value of 0.622 underscore the structural challenges Chinese cities face in green transformation—specifically, how to reduce emissions under conditions of high industrialization. Furthermore, authorized patents fluctuate widely between 4.248 and 12.715, and the average science and technology investment is only 0.267, indicating an uneven distribution of innovation capacity that may lead to significant heterogeneity in how the ETS policy enhances efficiency through technological pathways.

Table 3 presents the descriptive statistics for sample variables in both pilot and non-pilot areas before and after the policy implementation. Table 3 reveals that following the implementation of the pilot ETS, both pilot and non-pilot provinces experienced a decline in the proportion of the secondary industry and economic growth. Conversely, there was an increase in the science and technology investment and patent authorizations.

Table 4 provides a comparison of indicators using synthetic control, with Tianjin as the case study. Although the differences in some variables between synthetic Tianjin and treated Tianjin exceed the mean of 24 control groups, the synthetic control group's fit outperforms the mean in terms of comprehensive efficiency, proportion of fixed assets, science and technology investment, urbanization rate, and economic growth

Table 3
Descriptive statistics of sample variables in pilot areas and non-pilot areas before policy implementation.

Variable	Non-pilot period (2003–2012)		Pilot period (2013–2020)	
	Non-pilot	Pilot	Non-pilot	Pilot
Comprehensive efficiency	0.994	1.077	1.119	1.170
GDP(Ln)	5.924	6.192	7.079	7.434
Economic growth rate	12.391	12.486	6.908	6.983
Proportion of the secondary industry	48.112	45.318	40.453	36.233
Urbanisation level	49.142	68.053	60.510	75.569
Proportion of fixed assets	0.578	0.463	0.588	0.440
Proportion of science and technology investment	0.255	0.423	0.286	0.486
Proportion of environmental-protection expenditure	0.690	0.445	0.479	0.404
Energy structure	0.689	0.482	0.517	0.338
FDI foreign investment amount	1.878	2.922	3.407	4.621
Number of patents authorised (Ln)	8.594	9.676	10.027	11.042
Number of college students per 100000 people(Ln)	7.596	8.073	8.823	9.060

Table 4
Comparison of indicators constructed by synthetic control taking Tianjin as an example.

	Tianjin		Provincial mean value of 24 control
	Treated	Synthetic	
GDP(Ln)	5.738	5.613	6.292
Economic growth rate	16.017	13.676	10.237
Proportion of the secondary industry	54.500	46.513	45.971
Urbanisation level	78.858	54.075	49.210
Proportion of fixed assets	0.585	0.618	0.614
Proportion of science and technology investment	0.483	0.285	0.222
Proportion of environmental-protection expenditure	0.222	0.671	0.626
Energy structure	0.508	0.770	0.671
FDI foreign investment amount	3.533	2.603	2.187
Number of patents authorised (Ln)	9.184	8.482	8.888
Number of college students per 100000 people(Ln)	7.853	7.789	8.006
Comprehensive efficiency (2007)	1.132	1.120	1.025

Note: Only the comparison results of indicators in the Tianjin benchmark analysis are reported here because of the limited space.

rate for 2007. This study selects the optimal weights to minimize the disparity in overall effectiveness between the experimental and control groups. However, the comprehensive efficiency in 2007, as calculated with these weights, shows only a slight difference from that of Tianjin. Consequently, this weight combination is adopted as the counterfactual for Tianjin. Similarly, the same synthetic control group selection method is applied to the other five pilot areas.

3.2. Research method

3.2.1. Efficiency of urban green development based on the DEA model

DEA, a decision-making method proposed by Charnes and Rhodes in 1978, evaluates the relative effectiveness of similar departments or units. This method assesses the relative efficiency of decision-making units with multiple inputs and outputs using mathematical programming [51]. The principle of DEA involves using mathematical computations to determine a relatively efficient production frontier, ensuring the characteristics of statistical data remain unchanged by maintaining consistent inputs or outputs. Each unit is projected onto this production frontier, and its efficiency is evaluated by measuring the distance to the frontier.

As a method for evaluating relative efficiency, DEA results rely on reference technology, which in turn depends on sample selection. If samples vary or consist of the same individuals across different periods, the reference technology changes accordingly. Consequently, evaluation results derived from differing reference technologies are incomparable and non-transferable. Efficiency evaluations often utilize panel data. The central challenge is selecting appropriate samples and reference technology for temporal efficiency measurements. In the fixed reference method, efficiency values are derived by using data from period t, with period f serving as the fixed reference. This approach addresses the issue of non-comparability and non-transferability across different periods.

Current literature primarily employs the stochastic frontier analysis (SFA) and Data Envelopment Analysis (DEA) to measure green development efficiency [15]. The SFA method requires predefined production function specifications and is not suitable for scenarios involving multiple inputs and outputs. In small sample sizes, it may lead to estimation errors. In contrast, DEA and its derivative models offer the advantage of evaluating multiple outputs or input factors simultaneously [54]. Therefore, this study adopts the DEA model to calculate Urban Green Development Efficiency (UGDE). Under given input conditions, higher expected outputs and lower unintended outputs indicate greater

efficiency. Based on previous literature [15–17,55], this paper sets input and output indicators (shown in Table 5). The model's input indicators are categorized into three groups: capital factors, labor factors, and resource factors. Output indicators are classified into two types: expected outputs, primarily economic benefits, and unexpected outputs, including regional CO₂ emissions, industrial SO₂ emissions, industrial sewage discharge, and industrial smoke and dust emissions.

3.2.2. Synthetic control method

In empirical economics, identifying policy effects typically involves finding a counterfactual control group that mirrors the experimental group but without the exogenous shock. This concept stems from Hume's theory of causality. Comparing the experimental and control groups reveals the causal effect. Building on this concept, Abadie et al. (2003) introduced the Synthetic Control Method (SCM). The fundamental assumption of this method is that a linear combination of several non-pilot areas can approximate the counterfactual for the pilot area. Numerical methods are employed to optimize the weights in this model. Subsequently, parameters from the pilot area and its counterfactual are compared pre- and post-event. According to Liu [56], the optimal parameter is the variable in the pilot area before the event that best fits the corresponding variable in the counterfactual. According to existing research progress, the synthetic control method has been widely used in the fields of the impact of carbon trading pilot on industrial structure upgrading [1], the evaluation of policy effects of low-carbon pilot [35, 50], and the carbon emission reduction policy effects of China's carbon emission trading pilot [39]. In this study, SCM is applied to assess the impact of ETS construction on green development efficiency in the test area. The goal of optimizing weights for the composite control group is to minimize the mean square error in estimating green efficiency in the pilot area prior to policy implementation. This study analyzes green development efficiency data from C+1 cities over T years. Assuming ETS construction occurred only in the first city and not in the remaining C cities, the synthetic control group is selected from those C cities. E_{it}^N is set as the green development efficiency of City i ($1 \leq i \leq J+1$) at the end of Year t ($1 \leq t \leq T$) without the construction of the ETS. T_0 ($1 \leq T_0 < T$) is set as the year before the ETS construction pilot, and E_{it}^i is set as the green development efficiency of city i in year t ($T_0+1 \leq t \leq T$) after the ETS construction pilot.

α_{it} is set as the impact of the ETS construction pilot on the efficiency of green development; D_{it} is set as a virtual variable whether the construction of the ETS is conducted in city i in year t . Therefore, the following is obtained:

$$E_{it}^i = E_{it}^N + \alpha_{it} D_{it},$$

$$D_{it} = \begin{cases} 1 & i = 1, t > T_0 \\ 0 & \text{other} \end{cases} \quad (2)$$

Thus, when $t > T_0$, the impact of the ETS construction pilot on the green development efficiency of city i is

Table 5
Input-output sheet of urban green development efficiency.

Type	Grade I	Grade II	Grade III
Input	Capital factor	Fixed capital stock	Total investment in fixed assets
	Labor factor	Unit number of employees	Unit number of employees at the end of the year
Output	Resource factor	Energy consumption	Total energy consumption
	Expected output	Economic benefits	GDP (2002 constant price)
	Unexpected output	Environmental pollution	Regional CO ₂ emission, industrial SO ₂ emission, industrial sewage discharge, and industrial smoke dust emission

$$\alpha_{it} = E_{it}^i - E_{it}^N = E_{1t} - E_{1t}^N. \quad (3)$$

In Eq. (3), E_{1t} refers to the efficiency of green development in ETS construction pilot areas; E_{1t}^N refers to the efficiency of green development if ETS construction has not been initiated in the pilot areas. To estimate the green development efficiency in the pilot areas without ETS construction, this study refers to the research conclusions of Abadie et al., in 2010. An optimal weight combination forms a synthetic control group, approximating the counterfactual for the pilot areas. Therefore, the green development efficiency of this control group can be the unbiased estimation result of E_{1t}^N . Under these assumptions, and referring to the factor model based on parameter regression proposed by Abadi [57] as well as the model setting of Liu [56] on the carbon emission reduction effect of carbon emission trading pilot projects, the green development efficiency of the pilot areas without ETS construction E_{it}^N is quantified using a factor model:

$$E_{it}^N = \sigma_t + \theta_t Z_i + \lambda_t \mu_i + \varepsilon_{it} \quad (4)$$

In Eq. (4), σ_t refers to the period fixed effect of green development efficiency; θ_t refers to the $1 \times r$ dimensional parameter vector; Z_i refers to the vector composed of r variables that are not affected by the ETS construction pilot in control variables; λ_t refers to the $1 \times F$ dimensional unknown common factor vector; μ_i refers to the $F \times 1$ dimensional regional fixed effect; and ε_{it} refers to the stochastic disturbance term.

The above is the theoretical framework of SCM, and the next part is the weight combination estimation. In consideration of a $J \times 1$ dimensional weight vector $W = (w_2, w_3, \dots, w_{J+1})$ meeting all $w_j \geq 0$ and $\sum_{j=2}^{J+1} w_j = 1$, each w_j in the potential weight vector W of the synthetic control group represents the contributions of the remaining J cities to the synthetic control group. Thus, Eq. (4) can be obtained by the weighted mean of this weight.

$$\sum_{j=2}^{J+1} w_j E_{jt}^N = \sigma_t + \theta_t \sum_{j=2}^{J+1} w_j Z_j + \lambda_t \sum_{j=2}^{J+1} w_j \mu_j + \sum_{j=2}^{J+1} w_j \varepsilon_{jt} \quad (5)$$

Under the assumption that a potential weight vector $W^* = (w_2^*, w_3^*, \dots, w_{J+1}^*)$ exists and can form an optimal synthetic control group in the cities where the ETS construction pilot has been implemented, the following conditions are met:

$$\sum_{j=2}^{J+1} w_j^* E_{j1} = E_{11}, \quad \sum_{j=2}^{J+1} w_j^* E_{j2} = E_{12}, \quad (6)$$

$$\sum_{j=2}^{J+1} w_j^* E_{jT_0} = E_{1T_0}, \quad \sum_{j=2}^{J+1} w_j^* Z_j = Z_1. \quad (7)$$

According to Abadie et al. [57], with the assumption that the matrix $\sum_{t=1}^{T_0} \lambda_t' \lambda_t$ is full rank, $E_{1t}^N - \sum_{j=2}^{J+1} w_j^* E_{jt}$ can be proven to approach 0, i.e., $\sum_{j=2}^{J+1} w_j^* E_{jt}$ is the unbiased estimation of E_{1t}^N . Therefore, after the construction of ETS pilots, that is, $T_0 < t \leq T$, we can simulate the counterfactual substitute by using the green development efficiency of the synthetic control group. Thus, $\hat{\alpha}_{it} = E_{1t} - \sum_{j=2}^{J+1} w_j^* E_{jt}$ can be used as the unbiased estimation of the impact of the ETS construction pilot on the green development efficiency of city i .

4. Results and discussions

Table 4 presents the weight distribution used to construct the synthetic control group for each pilot region, with Tianjin serving as a representative case. This table outlines the specific weights assigned to donor provinces in modeling Tianjin's counterfactual trajectory. The impact of the ETS policy is assessed by comparing the green development efficiency (GDE) of each pilot region to that of its corresponding synthetic control unit. In the case of Tianjin, the ETS was implemented

in 2014. To construct its synthetic control group, variables such as the natural logarithm of GDP, technological assets, human capital, and other relevant indicators were used.

The estimated effects of the ETS are captured by the divergence in GDE between each pilot city and its synthetic counterpart in the post-2014 period. Following the approach of Abadie et al. [57], the weights for constructing synthetic controls are selected to minimize the mean squared prediction error in GDE during the pre-treatment period.

Table 6 details the specific weight composition for each synthetic control unit. Tianjin's synthetic counterpart draws primarily from Inner Mongolia, Jiangsu and Hainan. Similarly, Shanghai's synthetic control is based on Inner Mongolia and Hainan; Chongqing's on Liaoning, Jiangxi, Shaanxi, and Ningxia; Guangdong's on Zhejiang and Hainan; Beijing's solely on Zhejiang; and Hubei's on Jiangsu, Shandong, Sichuan, and Guangxi.

Some pilot cities lack close provincial analogues in the donor pool, which affects the quality of the synthetic match. As a result, the model achieves a good fit for Tianjin, Chongqing, Guangdong, and Hubei. However, the model fit for Beijing and Shanghai is less ideal, mainly because their urban development degree, economic development level and energy saving technology level are among the top in China, and other provinces and cities cannot match the carbon emission level of Beijing and Shanghai.

Fig. 1 displays the synthetic control results for six provinces in pilot areas. A primary objective of this study is to determine the optimal weights for Tianjin, Shanghai, Chongqing, Guangdong, Beijing, and Hubei. Additionally, the study seeks to observe changes in green efficiency differences between each pilot area and its corresponding synthetic control group following the implementation of the ETS. The following figure presents the green efficiency of each ETS pilot and its synthetic control province from 2003 to 2020. A vertical dotted line in the figure marks the year the carbon emission rights policy was implemented. To the left of the dotted line, the green efficiency of many provinces closely aligns with that of their synthetic control counterparts. To the right of the dotted line, the green efficiencies begin to diverge significantly.

Fig. 1 illustrates a rising trend in Shanghai's comprehensive efficiency, surpassing that of the control group by 2016, suggesting that the ETS construction positively influenced green trading in Shanghai. Prior to the carbon emissions trading pilot, the green efficiency of Beijing and Shanghai was significantly higher than that in other provinces and cities

[58]. Additionally, achieving a perfect fit through the weighting of other provinces and cities is challenging due to Shanghai's unique economic characteristics. Consequently, identifying suitable control groups for Shanghai is problematic. These findings align with those reported by Liu [56]. It is unclear whether these differences are due to the fitting process or the carbon emission pilot policy. This highlights the inherent limitations of SCM in evaluating specific policy effects: when regions with extreme characteristics exist, it may be challenging to construct an ideal counterfactual control group. Although the unique characteristics of Beijing and Shanghai pose challenges for SCM application, they do not undermine the core conclusion that ETS demonstrates overall positive effects. For policy implementation in non-first-tier cities, analyses based on other pilot programs still hold significant reference value.

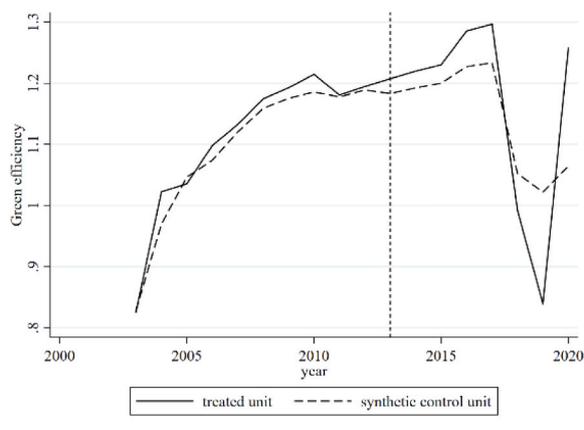
Green efficiency improved moderately in the four other pilot areas. However, in three of these areas, excluding Guangdong, green efficiency deviated from their respective control groups. Carbon dioxide emissions in Tianjin significantly decreased after 2013 (Hu, 2019). Additionally, Tianjin's green efficiency began diverging from its synthetic counterpart even before the ETS was constructed. Given Tianjin's status as the second-largest city in the Beijing-Tianjin-Hebei triangle and its proximity to the capital, it is reasonable to assume that Beijing's policies significantly influenced Tianjin. Consequently, Tianjin deviated from its synthetic counterpart earlier than anticipated (Nie, 2020). Chongqing's green comprehensive efficiency improved around 2015, with a marginal growth rate nearly matching that of its synthetic group. After 2013, the difference in green efficiency between Guangdong and its control group was negligible, as both showed simultaneous improvements. Hainan and Zhejiang contributed most significantly to the synthetic Guangdong. Hainan has maintained strong green development, while Zhejiang, a key player in the Yangtze River Delta, leads in policy transmission efficiency [59]. The discrepancy in green efficiency between Guangdong and its synthetic control is minimal.

The difference in green efficiency in Hubei Province first emerged in 2010 and has remained relatively stable since. A likely reason is that Hubei, being landlocked, has overlooked environmental costs, particularly those associated with FDI [60]. Consequently, despite a slight reduction in carbon emissions following ETS implementation, environmental protection in Hubei remains underprioritized. Significant improvements in Hubei's comprehensive green efficiency are challenging (Wei, 2020). According to some scholars, Hubei has achieved the most effective emission reductions within the Yangtze River Economic Belt

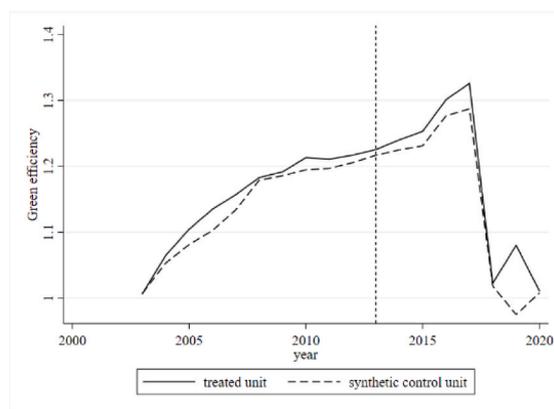
Table 6

Weight sheet of the synthetic control group in pilot areas.

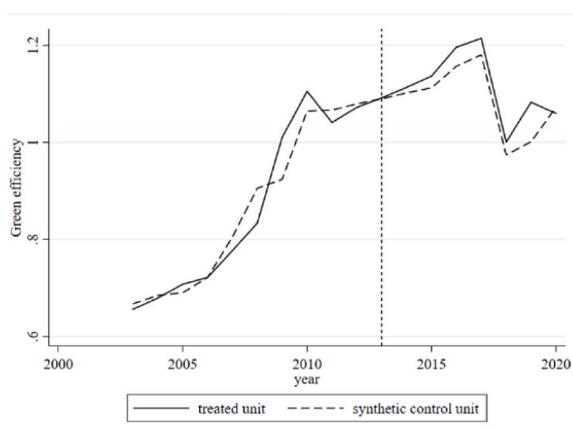
Provinces	Tianjin	Shanghai	Chongqing	Guangdong	Beijing	Hubei
Hebei	0	0	0	0	0	0
Shanxi	0	0	0	0	0	0
Inner Mongolia Autonomous Region	0.386	0.051	0	0	0	0
Liaoning	0	0	0.159	0	0	0
Jilin	0	0	0	0	0	0
Heilongjiang	0	0	0	0	0	0
Jiangsu	0.326	0	0	0	0	0.179
Zhejiang	0	0	0	0.914	1	0
Anhui	0	0	0	0	0	0
Fujian	0	0	0	0	0	0
Jiangxi	0	0	0.372	0	0	0
Shandong	0	0	0	0	0	0.017
Henan	0	0	0	0	0	0
Hunan	0	0	0	0	0	0
Guangxi	0	0	0	0	0	0.175
Hainan	0.288	0.949	0	0.086	0	0
Sichuan	0	0	0	0	0	0.63
Guizhou	0	0	0	0	0	0
Yunnan	0	0	0	0	0	0
Shaanxi	0	0	0.093	0	0	0
Gansu	0	0	0	0	0	0
Qinghai	0	0	0	0	0	0
Ningxia	0	0	0.375	0	0	0
Xinjiang	0	0	0	0	0	0



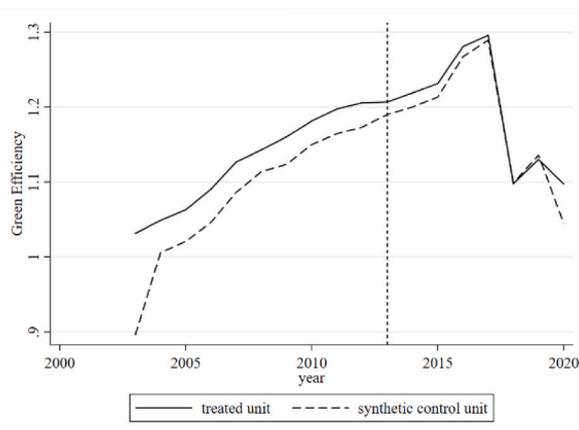
(a) Tianjin



(b) Shanghai



(c) Chongqing



(d) Guangdong

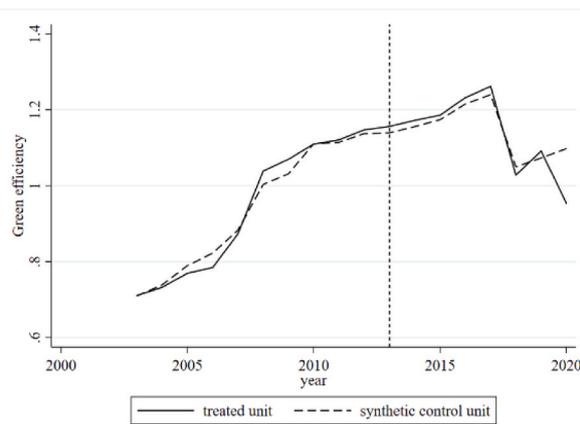
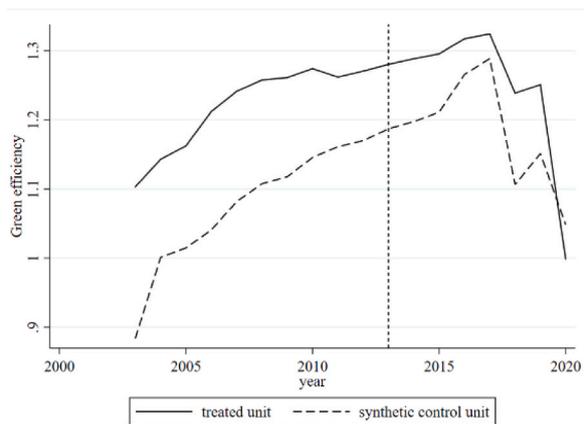


Fig. 1. Synthetic control results in pilot areas.

(Zhang, 2020). Following the ETS pilot, significant reductions in carbon emissions were observed in Hubei's transportation (Lu, 2020) and power sectors (NIE, 2020). However, this study identifies two factors contributing to the minimal impact of the ETS pilot on Hubei's comprehensive green efficiency. Firstly, optimal weight estimation is hindered by the limited number of provinces and control variable constraints, affecting the fitting quality. Secondly, the ETS policy impacts various sectors in Hubei in differing extents. Consequently, no significant difference in comprehensive green efficiency is observed between Hubei and its

synthetic counterpart post-ETS pilot. FDI not only introduces advanced management concepts and technologies but also leads to high industrial concentration, particularly in processing and assembly manufacturing (Jiang, 2002). Advanced technology from FDI significantly influences the optimization of local industries [61]. However, many industries in China are low-value-added with minimal investment in advanced technology and smart production. Consequently, FDI's impact on modernizing local industrial infrastructure is limited [53]. All regions saw an increase in comprehensive green efficiency around 2015, likely

due to the Interim Measures for Carbon Emission Trading implemented on December 30, 2014, which bolstered the national carbon trading market and enhanced overall green efficiency [62].

Following the launch of the carbon trading pilot, the trajectories of actual and synthetic comprehensive efficiency in the pilot areas of Tianjin, Shanghai, Chongqing, and Hubei began to diverge. As depicted in Fig. 1, the solid lines representing actual efficiency are consistently above the dotted lines for synthetic efficiency. The findings reveal that in all four pilot districts, actual comprehensive efficiency exceeds that of their synthetic counterparts. However, the timing of the divergence between actual and synthetic efficiency paths varies across the pilot areas: Tianjin around 2012, Shanghai around 2016, Chongqing in 2015, and Hubei in 2010. Pilot regions differ in economic endowments, intensity of policy implementation, and efficiency of policy transmission.

Regarding the fluctuations and anomalies in green development efficiency after 2018, the phenomena can be analyzed from several dimensions. First, the outbreak of the China-US trade war imposed a direct shock on export-oriented industries in coastal pilot regions such as Shanghai, Guangdong, and Tianjin. Trade barriers compressed corporate profit margins, potentially forcing firms to reduce non-productive R&D investments in green technologies, which suppressed green efficiency in the short term. Second, from a policy cycle perspective, the official launch of the national carbon market at the end of 2017 signaled a transition period for local pilots to align with the national system, and increased policy uncertainty may have led to a temporary decline in market activity. Finally, the COVID-19 pandemic in 2020 caused severe shocks to urban socioeconomic operations, leading to drastic fluctuations in industrial output and impaired resource allocation efficiency. Nevertheless, the actual efficiency in most pilot areas remained higher than that of the synthetic groups, demonstrating the resilient support of environmental regulatory policies for green development under extreme external shocks.

5. Robustness test

5.1. Counterfactual analysis

The pilot ETs were implemented in these areas in 2013, and SCM was used to construct counterfactual substitutes to verify if the conclusions from pilot areas hold. The placebo test relies on a key hypothesis: the experimental group (pilot areas) and the control group (counterfactual substitutes) share similar characteristics and exhibit a good fit in 2013 before the ETS implementation. Results indicate that SCM could not properly construct synthetic controls in some provinces before 2013, impacting the placebo test's effectiveness. Consequently, this study will assess the fit between pilot areas and their counterfactuals using mean squared prediction error (MSPE), excluding provinces where synthetic controls are inadequate. MSPE5 denotes provinces whose MSPE is five

times higher than that of the control group; these provinces are excluded. Similarly, MSPE2 applies to provinces with MSPE twice that of the control group; these are also excluded. Provinces unable to form valid SCM counterfactuals before 2013 were excluded. This exclusion streamlined the control group, reducing policy influence on nonpilot areas and broadening the pilot study's scope. For instance, provinces such as Sichuan, Zhejiang, and Jiangsu were included in the experimental group, with all other conditions held constant. Analysis of green efficiency trends showed that Tianjin's policy had the most effective fit, hence its selection as a case study in this research.

In Fig. 2, the black line represents the treatment effect in Tianjin—specifically, the difference in mean green efficiency between Tianjin and its synthetic counterpart. The grey line indicates the placebo effect in other control provinces, showing their green efficiency differences relative to their synthetic controls. According to Fig. 2, prior to 2013, the green efficiency difference between Tianjin and its counterfactual was minimal, fluctuating around zero. This fit is more accurate than those observed in other provinces. After 2013, the increase in mean green efficiency in Tianjin exceeded the positive effects observed in other control groups. The results demonstrate that the ETS pilot positively impacted Tianjin's green development efficiency, suggesting a stable and robust causal relationship. However, the observed fluctuations in green efficiency during the 2018–2019 period can be partially attributed to the outbreak of the China–US trade war, which imposed external economic shocks on industrial production and resource allocation. These trade-related uncertainties likely compressed corporate profit margins and temporarily diverted investments away from green technological innovation, leading to the anomalous data points observed in the late sample period.

5.2. Placebo test

To confirm the validity of our conclusions, a placebo test was conducted to ascertain whether the observed improvements in green development efficiency in pilot areas can be attributed solely to the ETS implementation. The placebo test involves selecting a group of unexpected cities and assuming these cities implemented the ETS, using SCM for analysis. If post-2013 green development efficiency in these cities significantly exceeds their synthetic controls, it would indicate that our study's conclusions might not be robust.

For the placebo test, areas with green development efficiency comparable to the six pilot provinces were chosen as sham reform regions, specifically those contributing most in the weight combinations [63], such as Tianjin–Inner Mongolia and Shanghai–Hainan. Considering the recurrence and significance of contributions, Inner Mongolia, Sichuan, and Hainan were selected as sham experimental groups. Lastly, SCM analysis was performed in these areas with the original pilot timing and control variables maintained.

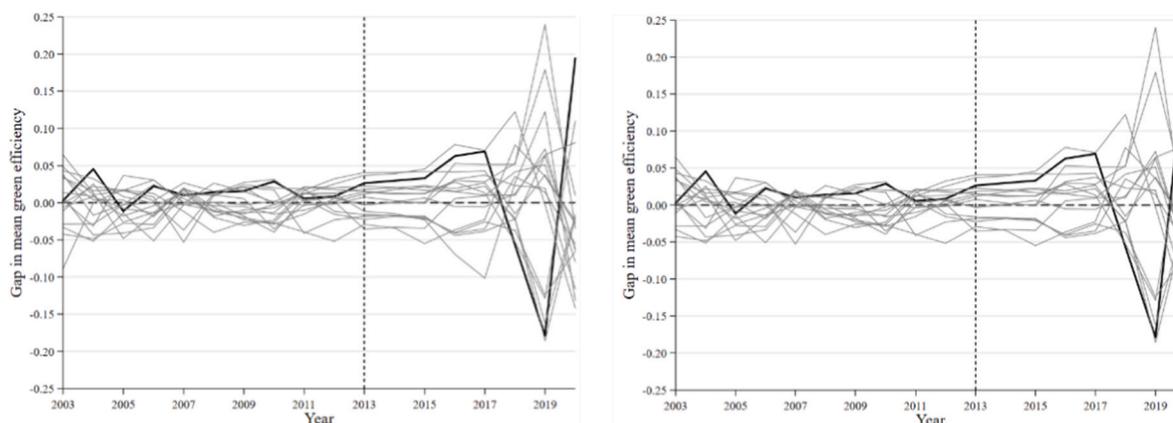
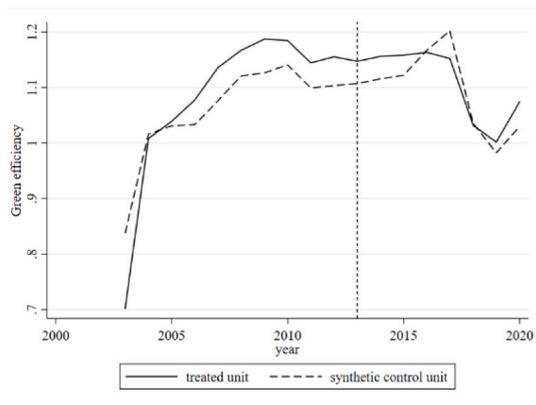


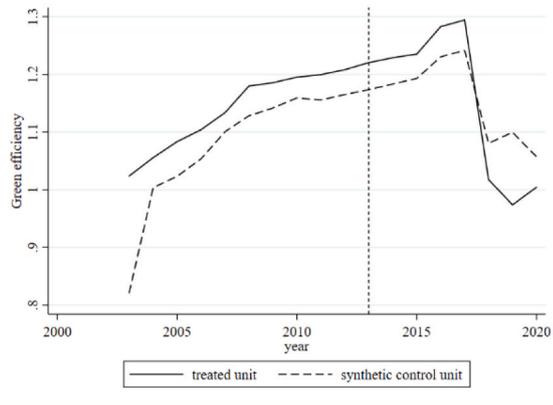
Fig. 2. Synthetic Tianjin distribution after eliminating control groups iteratively.

Fig. 3 shows that the green development efficiency in three experimental groups has shown minimal improvement since 2013. Since 2013, Inner Mongolia's green development efficiency has not improved; it has actually decreased. The synthetic control for Hainan shows a less

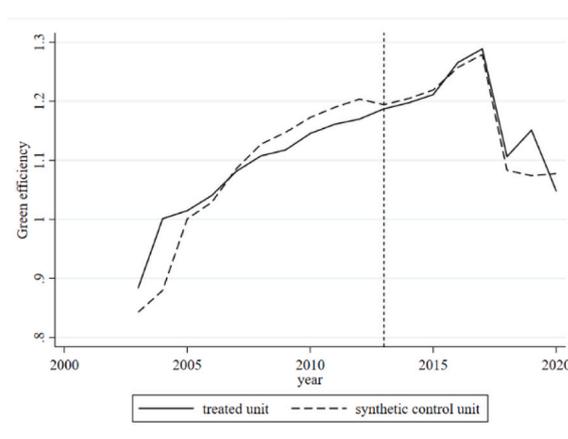
effective fit compared to the other two regions. Before 2013, Hainan's green development efficiency was higher than its control group, but it exhibited a marginal decreasing trend thereafter. After 2013, the gap in green development efficiency between Hainan and its control group



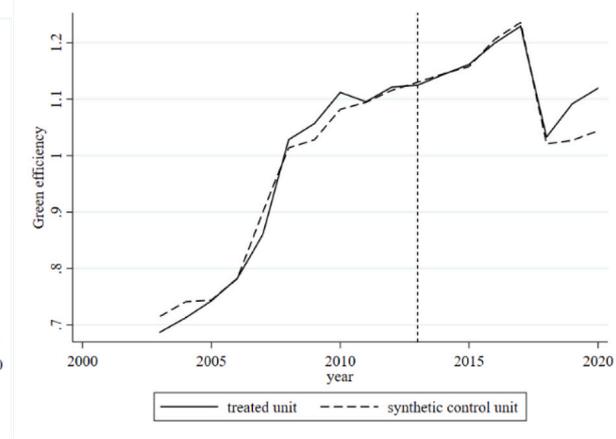
(a) Inner Mongolia (Tianjin)



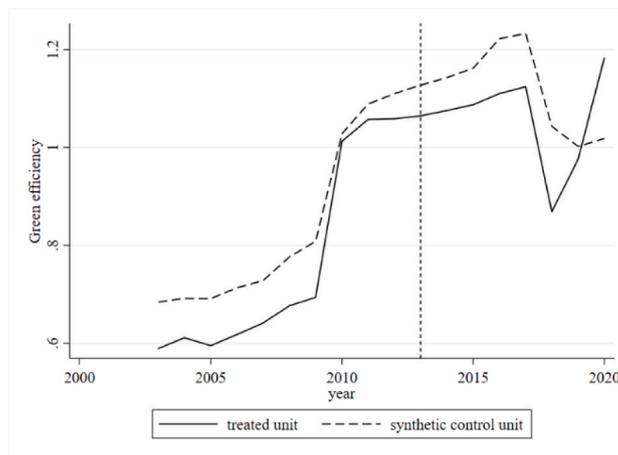
(b) Hainan (Shanghai & Beijing)



(c) Zhejiang (Guangdong)



(d) Sichuan (Hubei)



(e) Ningxia (Chongqing)

Fig. 3. Placebo test results.

narrowed consistently. The synthetic control for Sichuan fits well, showing virtually no difference in green efficiency before and after 2013. This finding confirms that without the implementation of carbon emission trading, there is little to no improvement in green efficiency, indicating that the gains in pilot areas are due to ETS implementation. Therefore, the conclusions are robust.

6. Mechanism analysis

The construction of the ETS may improve comprehensive green efficiency via two potential mechanisms: technological innovation and industrial structure optimization. ETS incentivizes enterprises to pursue technological innovation and optimize industrial structures, which is further facilitated by increased foreign direct investment (FDI) and other factors. Technological innovation and industrial structure optimization interact to enhance green comprehensive efficiency in pilot areas (Yuan and Xie, 2016; [1]).

6.1. ETS and proportion of investment in science and technology

This study employs SCM across six pilot provinces to analyze the impact of ETS on science and technology investment proportions. Control variables include urban GDP, urban population size, FDI, the

number of college students per 10,000 people, the proportion of the industrial structure and industrial waste emissions.

The impact of science and technology investment is quantified by the number of patent applications, serving as a proxy for such investments. Fig. 4 illustrates the increase in patent applications in each ETS pilot area following the introduction of the carbon trading pilot. This suggests that ETS implementation has, to some extent, promoted technological innovation in enterprises. Consequently, enterprises may reduce costs or boost revenue by enhancing product quality, thereby ensuring healthy cash flow and better operating performance (Song et al., 2019). Technological innovation inherently reduces carbon emissions and enhances green comprehensive efficiency. Fig. 4 shows that the number of patented inventions in Tianjin and Chongqing increased significantly, indicating that the carbon emission trading system in Tianjin and Chongqing can improve technological inventions and thus further improve their green efficiency. In Hubei, the impact of technological innovation on green efficiency is minimal, aligning with the negligible changes observed in the region's green efficiency. Hubei's uneven economic development may explain the limited impact of technological innovation there. Thus, support cannot be obtained from the technological perspective. One possible explanation is that certain areas of Hubei have low GDP and green development efficiency, and other cities are experiencing a decline in green comprehensive efficiency.

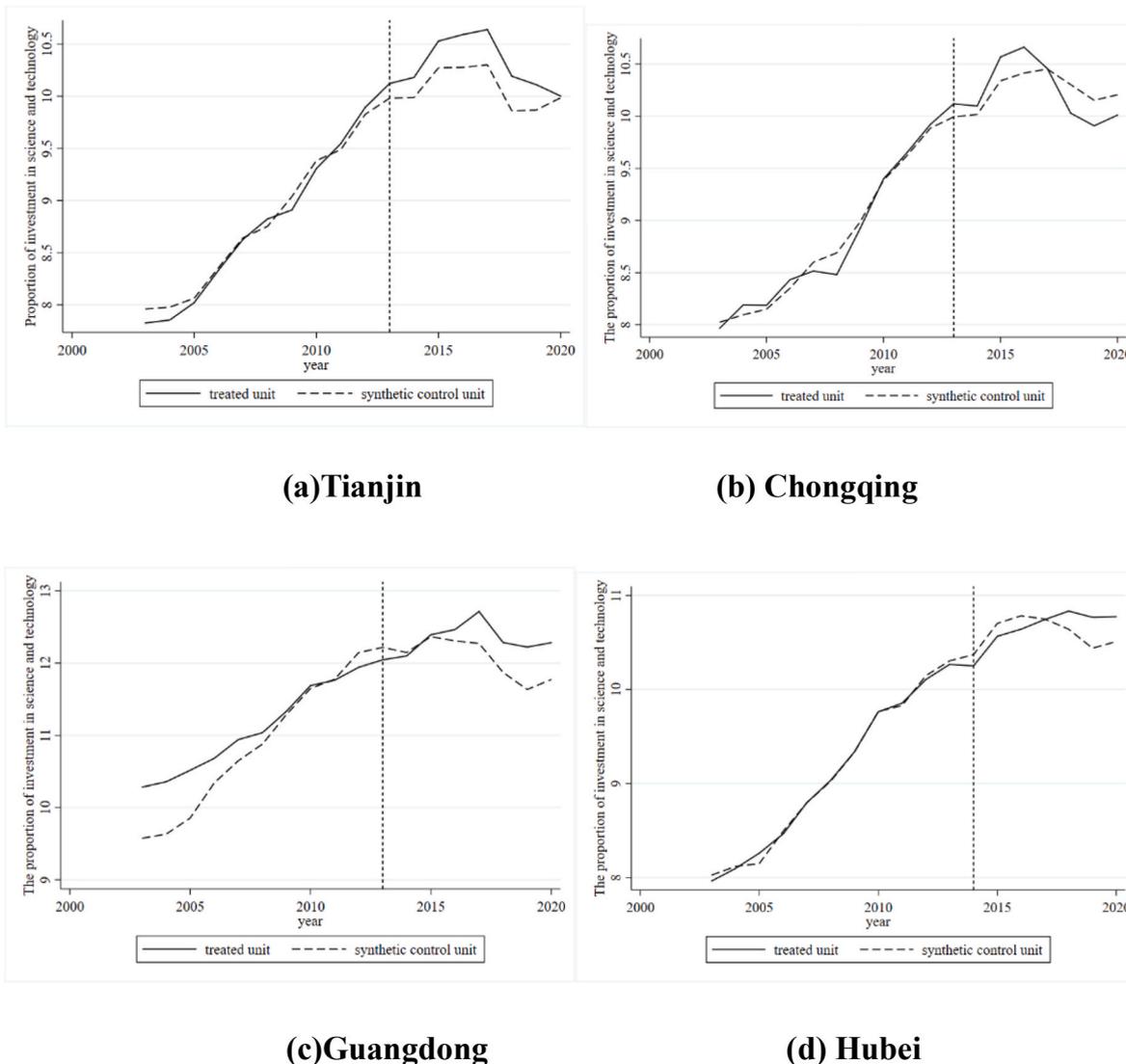


Fig. 4. Synthetic control results of the proportion of investment in science and technology based on the construction of ETS (mechanism 1).

Consequently, the increase in the number of patents in Hubei closely mirrors that of the synthetic control group(Wei, 2020). In Guangdong, the initial synthetic analysis shows a low impact of technological innovation. This likely results from including Shenzhen's ETS pilot, part of Guangdong, which may distort the synthetic control group for the province. There is a clarification on the relationship between several concepts and the specific situation in Hubei. Firstly, the implementation of carbon policies significantly contributes to technological advancements, enhancing green efficiency on a broader scale. Government regulations and incentives aimed at reducing carbon emissions and promoting sustainable practices drive businesses and researchers to develop more energy-efficient and environmentally friendly technologies. Consequently, these technologies positively impact green development and spur economic growth. Secondly, unbalanced economic development in Hubei has significant implications for technological innovation across the province. In Hubei, regional and industrial disparities have resulted in uneven technological advancements. Consequently, some areas in Hubei may lack sufficient investment in research and development, hampering technological and green efficiency progress. Thirdly, the unbalanced economic development in Hubei has likely contributed to low GDP and green development efficiency in the region. If sectors with high carbon footprints dominate without adequate investment in green technologies, this can stifle both economic and environmental progress. Lastly, the decline in four other cities, along

with patent trends mirroring the synthetic control group, suggests limited technological and green efficiency improvements in these areas. This observation suggests that, despite implementing carbon policies, their impact on technological advancement and green efficiency in these cities has been limited. It can be inferred that although carbon policies generally promote technological innovation and enhance green efficiency, their effectiveness varies based on regional economic conditions and investment priorities. In Hubei, uneven economic development may have impeded progress in green efficiency and technological innovation, especially in areas with insufficient focus on environmental protection and R&D. The dominance of carbon-intensive industries in Hubei, contributing to its low GDP and green development efficiency, has stifled the transition to more sustainable practices. The decline in certain cities and patent trends mirroring the synthetic control group suggest that carbon policies have not yet to significantly boost green efficiency and technological innovation in these areas.

6.2. ETS and industrial structure

This study primarily investigates whether the ETS pilot program impacts the comprehensive green efficiency of pilot regions through industrial structure transformation. SCM is applied in the six pilot regions to analyze how industrial structure influences ETS development. Control variables in the industrial structure model include urban GDP,

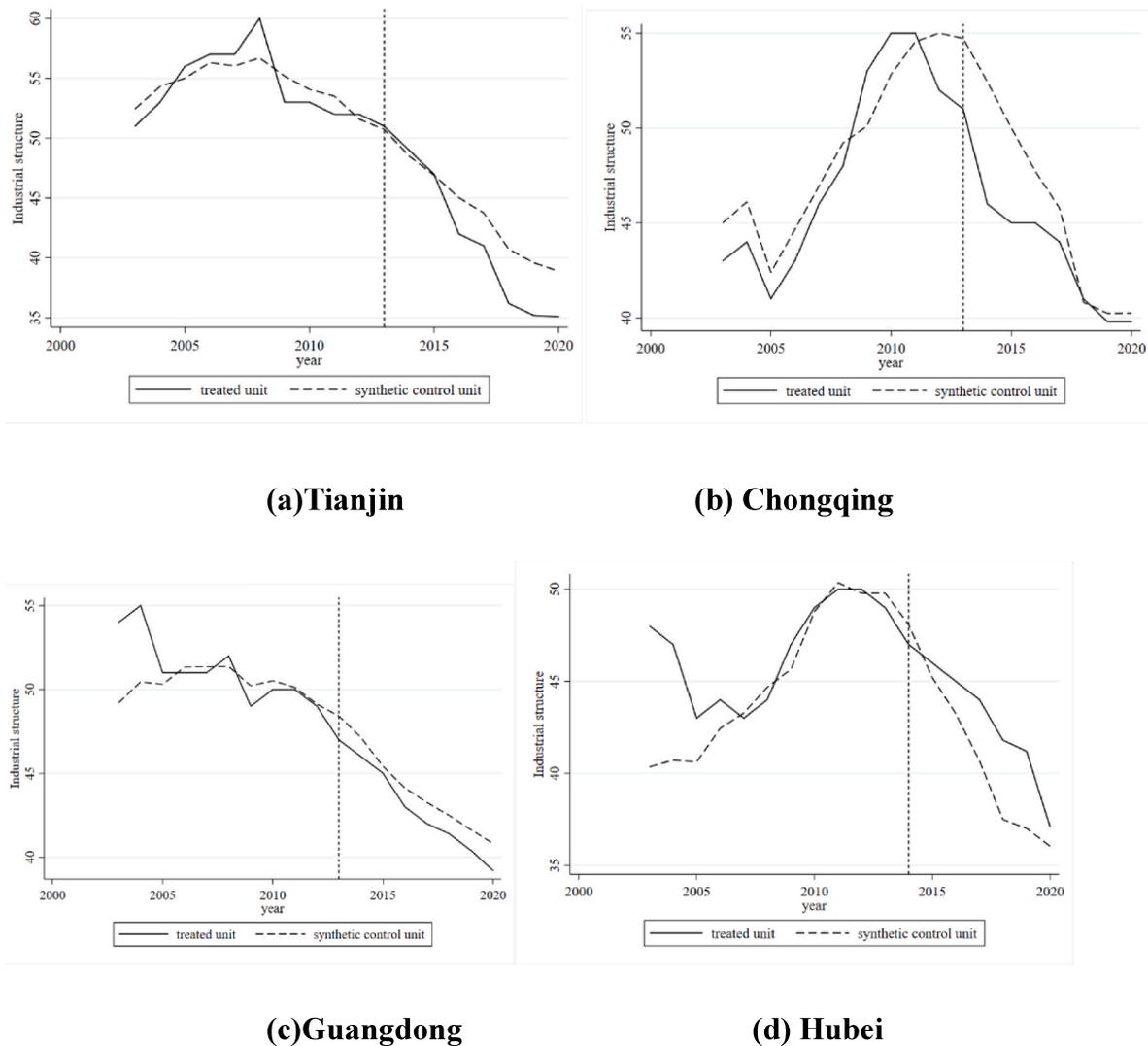


Fig. 5. Synthetic control results of the change of industrial structure based on the construction of ETS (mechanism 2).

population size, FDI, science and technology investment, and fixed asset investment.

Fig. 5 illustrates a slight decline in the proportion of the secondary industry in Tianjin around 2015, which increasingly diverged from its synthetic control group. This suggests that the ETS played a significant role in optimizing Tianjin's industrial structure. In Chongqing, the proportion of the secondary industry began to decline in 2011, likely influenced by the city's robust tourism sector and a predominance of light industry within the secondary sector. Consequently, Chongqing's secondary industry appears to be more responsive to ETS initiatives. However, Chongqing's ETS trading volume remains low, possibly due to market participants making preemptive adjustments and recalibrating their expectations in anticipation of ETS impacts, thereby reducing the secondary industry's share.

Before the ETS implementation, notable differences existed between the share of the secondary industry in Guangdong and its synthetic control group. This discrepancy arose because Shenzhen, a distinct ETS pilot within Guangdong, skews the synthetic control group for the province, as noted in earlier studies. Following the pilot, around 2012, the share of the secondary industry in Guangdong significantly decreased and aligned more closely with the synthetic control group. This aligns with findings from Yi et al. (2020), explaining why Guangdong's green efficiency remained unchanged post-pilot. In Hubei, the secondary industry's proportion exceeds that of the synthetic control. Consequently, the emission trading policy in Hubei has had a limited effect on enhancing green efficiency. In summary, industrial restructuring is a potential pathway for ETS to influence green efficiency. However, its realization and effectiveness vary considerably across pilot regions, contingent on local economic structures and conditions.

It is noteworthy that, as illustrated in Figs. 4 and 5, the policy effects of ETS on enhancing UGDE through technological innovation and industrial restructuring exhibit a reasonable time lag. Technological innovation typically requires several years to transition from R&D investment to patent application and practical implementation. At the same time, industrial restructuring involving the contraction of high-carbon sectors and expansion of low-carbon industries constitutes an even longer-term process. The analysis reveals that patent growth and industrial restructuring only significantly diverged from the synthetic control group after a period following the pilot program's launch, correlating with subsequent efficiency improvements, which are consistent with theoretical expectations. Lag periods may vary across regions depending on initial conditions and policy enforcement intensity, which partially explains regional differences in effectiveness outcomes.

While the analysis of patent activity and industrial restructuring sheds light on the transmission mechanisms of ETS, institutional constraints in certain sectors may significantly dampen firms' responsiveness to carbon pricing signals. In particular, it is crucial to consider the institutional context of China's energy governance when evaluating the effectiveness of ETS. Unlike in market-based economies where firms independently make investment decisions and respond to carbon price fluctuations, China's power and heating sectors remain heavily influenced by central planning. Key decisions—such as capacity expansion, technology adoption, system dispatch, and pricing—are determined administratively by government authorities rather than market forces. Consequently, power generators have limited autonomy to adjust their carbon strategies based on economic incentives. Their emissions profiles and technological pathways are largely shaped by top-down policy mandates rather than cost–benefit optimization. This institutional rigidity significantly weakens the transmission of carbon price signals in these sectors. As emphasized by the International Energy Agency [64], in systems where investment, dispatch, and pricing are centrally controlled, market-based carbon pricing mechanisms often struggle to induce meaningful behavioral change among regulated entities.

While our analysis highlights the role of technological innovation and industrial restructuring as key transmission channels through which

ETS improves urban green development efficiency, it is important to acknowledge that these mechanisms may also be influenced by external, co-occurring factors. During the same period as the ETS pilot implementation, several parallel developments—such as regional industrial upgrading initiatives, preferential fiscal or tax policies for green industries, foreign direct investment (FDI) inflows, and broader environmental governance reforms (e.g., the Air Pollution Prevention and Control Action Plan)—may have contributed to changes in innovation dynamics and industrial structure. These overlapping drivers could partially reinforce or confound the mechanism effects observed in our analysis. Although the use of the Synthetic Control Method helps mitigate biases from time-varying unobserved factors, it cannot fully eliminate the possibility of such interacting influences.

7. Conclusions and policy recommendations

The Emission Trading Scheme (ETS) is a crucial policy tool employed by the Chinese government to enhance energy conservation, reduce the societal costs of emission reduction, and foster technological advancement in enterprises. This study assesses the impact of the ETS on Urban Green Development Efficiency (UGDE) using the Synthetic Control Method (SCM) and Data Envelopment Analysis (DEA) models, leveraging China's ETS pilot policy as a quasi-natural experiment. Empirical analysis shows that the construction of ETSs has variably enhanced comprehensive green efficiency across different pilot areas. Robustness tests confirm that ETS construction positively impacts urban green development efficiency, substantiating a stable causal relationship. From a mechanistic perspective, ETSs likely enhance comprehensive green efficiency through technical innovation and changes in industrial structure, and there is a reasonable time lag in the effect of the policy. Based on these findings, this study provides the following recommendations:

Firstly, the scale of the ETS should be expanded, and the mechanism of the carbon trading market should be improved. Currently, both the development of China's ETS and the engagement of market participants are inadequate. Diversified enterprise participation can enhance market mechanism effectiveness, lower financial costs for businesses, and effectively mitigate risks [2]. Consequently, the ETS must be further expanded, and specific policies should be developed to integrate high-emission heavy industries into the market. Additionally, promoting the coordinated development of the ETS and the energy market is crucial to create synergies and ensure incentive compatibility, supporting the enhancement of China's carbon pricing mechanism.

Secondly, the development of the carbon emission trading market should be tailored to local environmental and resource conditions, with an emphasis on using financial tools to enable effective allocation of factors across regions. Considering the lower technical costs in firms, first-tier cities exhibit higher efficiency in policy transmission, larger market sizes, better aligned expectations, and larger ETS transaction volumes compared to smaller cities. For instance, Shanghai's carbon trading price-to-earnings ratio indicates a weakly efficient market, a benchmark that other pilot areas have not yet achieved [61]. Consequently, it is advisable to generalize Shanghai's carbon finance market strategies to other pilot regions, enhance participation from financial institutions including banks, insurance companies, trusts, and funds, and augment the efficiency of the carbon emission trading system with innovative financial products. Simultaneously, regulatory authorities need to strengthen oversight of carbon finance to ensure it remains aligned with its intended objectives. Furthermore, proactive measures should be implemented to foster technological innovation in heavy industries, which in turn would reduce the financial burden of emission reduction.

Thirdly, enterprises should be incentivized to adopt green and low-carbon technologies, embrace sustainable living and production practices, and initiate greening actions. China's targets for peaking emissions by 2030 and achieving carbon neutrality by 2060 present significant

challenges. Industries need to actively innovate and implement strategies to reduce carbon emissions, enhance land greening, and transform energy sources to meet these targets and increase 'green Total Factor Productivity' (TFP). Specifically, in the electric energy sector, there should be a gradual increase in the share of clean energy sources like hydropower, photovoltaic, and wind power. Additional policies are necessary to minimize carbon emissions from coal-fired power plants. The government should also prioritize building essential energy infrastructure, such as ultra-high voltage power grids, ahead of schedule, while enhancing electricity trading markets and boosting energy distribution efficiency.

While the empirical findings of this study provide robust evidence for the positive impact of the ETS on urban green development efficiency, it is important to acknowledge the methodological limitations inherent in the Synthetic Control Method (SCM). First, the validity of SCM results is highly dependent on the quality of pre-treatment fit between the treated unit and its synthetic counterpart. In cases where the donor pool fails to replicate pre-intervention trends—such as with Beijing and Shanghai—the causal interpretation becomes less reliable [57]. Second, although SCM can partially control for time-varying unobservable confounders through data-driven weighting, it may still be vulnerable to bias if omitted shocks influence both policy adoption and outcome trajectories [65]. Third, SCM lacks conventional inferential frameworks. It relies on placebo tests or permutation inference to assess significance, which limits statistical power and prevents the calculation of standard errors or

confidence intervals. These caveats should be considered when interpreting the findings and drawing policy implications.

Author statement

Yunjiang Yu: Conceptualization, Methodology, Writing, Software, Validation.

Yingying Zhang: Conceptualization, Methodology, Writing, Software, Validation.

Pengyu Zhu: Conceptualization, Methodology, Writing - Review & Editing.

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Declaration of competing interest

We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work, there is no professional or other personal interest of any nature or kind in any product, service or company that could be construed as affecting the position presented in, or the review of, the manuscript entitled.

Nomenclature list

ETS	Emission Trading Scheme
UGDE	Urban Green Development Efficiency
GHG	Greenhouse Gas
IEA	International Energy Agency
NDRC	National Development and Reform Commission
IETA	International Emissions Trading Association
TFP	Total Factor Productivity
DID	Difference-in-Difference
SCM	Synthetic Control Method
PSM	Propensity Score Matching
DEA	Data Envelopment Analysis
EU	European Union
GDP	Gross Domestic Product
SO ₂	Sulfur Dioxide
CO ₂	Carbon Dioxide
FDI	Foreign Direct Investment
MSPE	Mean Squared Prediction Error

Data availability

Data will be made available on request.

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