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Estimating the CO2 marginal abatement cost and implications for climate policies in China's industrial sector: A firm-level analysis

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ABSTRACT

This paper presents an in-depth analysis of the Marginal Abatement Cost Curve (MACC) for CO2 of China's industrial sector. Leveraging comprehensive firm-level panel data spanning the period 2011–2015, we employ a parameterized directional output distance function to estimate the shadow price of CO2. By doing so, we derive the marginal abatement cost for individual firms across different years, which provides crucial insights into two fundamental aspects: first, the variation in shadow prices as indicators of the economic efficiency of existing climate policies; and second, the carbon price levels necessary to achieve CO2 mitigation targets in the future. Furthermore, we conduct scenario simulations to assess the potential industrial output loss resulting from forthcoming carbon policies, such as the European Union's Carbon Border Adjustment Mechanism (CBAM). Our findings underscore the necessity for a considerably higher tax rate to stimulate pollution reduction in order to meet the desired emission targets.

KEYWORDS

Shadow price; marginal abatement cost curve; directional distance function; climate change; carbon tax

JEL CLASSIFICATION

H23; L51; L94; L98; Q48

1. Introduction

As the world's largest emitter of greenhouse gases, China has set various goals and commitments toward addressing climate change, including peaking its CO2 emissions by 2030 or earlier and achieving carbon neutrality (net-zero emissions) by 2060. To achieve these targets, China has made significant efforts to slow the rise in its greenhouse gas emissions. While the global community has welcomed this China-led initiative to address CO2 emissions, concerns have been raised about China's capacity and capabilities in achieving its climate change goals in times of uncertainty. Before the 2010s, China highly relied on strict regulation rather than market-based mechanisms in environmental governance (Guojun, Wang, and Zhang 2020; Karplus, Zhang, and Zhao 2021). Other studies have similarly suggested that flexible market-based instruments like cap-and-trade may help China meet its emissions targets at lower reduction costs (Cui et al. 2021). China's government also raises the importance of the market to play a decisive role in the economy and make economic development more sustainable. As a result, more

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consideration will be given to cost-effective solutions when exploring and identifying opportunities for reducing CO2 emissions in China in the future.

In economic policies centered around carbon trading and carbon taxes, price signals are crucially important. Understanding the effective carbon price that can drive emissions reductions not only helps determine the initial allocation prices of quotas in the carbon trading market and the rate of carbon tax but also facilitates further analysis of the economic impact of carbon neutrality policies, ultimately providing a scientific basis for implementing comprehensive economic policies. The Marginal Abatement Cost Curve (MACC), an economic tool that has gained significant traction in recent years, has emerged as a focal point of analysis and application in the realm of climate change policy. The MACC's rise in popularity can be attributed to its ability to simplify the intricate relationship between emissions abatement efforts and the associated marginal costs of reducing one unit of CO2 emissions. In the eyes of policymakers and scholars engaged in climate negotiations, the MACC serves as an illustrative guide, shedding light on the potential benefits of implementing emissions trading systems. It aids in the estimation of permit prices and carbon taxes, providing valuable insights for determining a solution that achieves the most cost-effective emissions constraint target.

While there have been notable studies investigating MACC in recent years, firm-level analyses of MACC of CO2 remain scarce, while they can provide valuable insights for informing nationwide climate policies in China. Specifically, it can assist policymakers in identifying the Marginal Abatement Cost (MAC) gap among sectors and regions and designing a burden-sharing strategy to achieve national emission reduction targets. This paper aims to fill this gap by adopting a novel strategy that involves identifying the optimal modeling specification from a set of competing specifications to develop a firm-level MACC for China. The method employed in estimating the MACC is empirically tractable and easy to solve, contributing to the practical applicability of the findings.

This paper tries to address the following questions: what is the marginal cost of pollution abatement for manufacturing firms in China? In achieving carbon mitigation constraints such as EU CBAM, what is the opportunity cost the industrial sector will have?

We develop a directional distance function approach to identify technical innovators in the area of CO2 emissions. Based on a unique firm-level emission dataset, we try to examine the effectiveness of environmental regulation in industrial pollution control. The score of technical efficiency was used as an indicator of firms' competitive capacity. We used non-parametric tests to examine the distribution and ranking of these two technical efficiency scores within industrial subsectors. All the test results rejected the null hypothesis that these two measurements were equal, resulting in the finding that environmental regulation did not cause enterprises to fully internalize environmental costs. We also examined the effect of some major factors influencing enterprises' environmental technical efficiency. The findings are as follows: (1) Export enterprises have lower marginal abatement cost of CO2 than their counterparts; (2) There is an increasing trend in MAC of CO2 between 2011 and 2015; (3) There is huge heterogeneity in MAC of CO2 among sectors; (4) the corresponding loss of industrial added value is estimated to be at least ¥2513.89 billion if EU CBAM is implemented.

This paper makes a notable contribution in several distinct ways. Firstly, it estimates firm-level Marginal Abatement Costs (MACs) in China, considering a given production-based technology, and subsequently develops a sector-level Marginal Abatement Cost

Curve (MACC) based on these firm-level MACs. This approach provides a nuanced understanding of the heterogeneity in MACs across sectors and regions, accounting for firm-level variations in economic structure, resource endowments, and technological capabilities. Secondly, this paper applies the newly proposed MACC estimation method as well as a rigorous comparison of MACC specifications to simulate the cost of carbon reductions in China for recent years (2011–2015). This empirical analysis carries important policy implications for China's low-carbon strategy, providing insights into the potential costs associated with achieving the country's emission reduction targets. The findings from this simulation exercise can inform policymakers in designing effective and economically efficient policies to address climate change mitigation at the national level, thereby contributing to the ongoing policy discourse on sustainable development and environmental stewardship. These contributions enhance our understanding of the economics of climate change mitigation in the context of China, and provide valuable insights for policymakers, researchers, and stakeholders engaged in formulating and implementing effective environmental policies.

The remainder of this paper is organized as follows: Section 2 introduces a brief policy review of climate policy in China and the incoming EU CBAM. Section 3 describes our methodology to estimate the shadow price of CO2. Section 4 details the dataset we use and the summary statistics of the variables. Then we provide the detailed estimation results and policy simulation in Section 5, and Section 6 concludes.

2. Policy background

2.1. China's climate policy background

The economy of China has experienced a huge transformation over the past four decades at the cost of the deterioration of the environment. Pollution and climate change issues started to become a major concern of the Chinese government in the 2000s. According to the International Energy Agency (2009), China has the highest carbon dioxide emissions and was responsible for 21% of the world's CO2 emissions from fuel combustion in 2007. Many cities in China are among the most polluted in the world and face serious public health hazards associated with environmental pollution. Exposure to elevated concentrations of either pollutant has been linked to significant human health and ecosystem damage. Studies have found that exposure to air pollution and extreme temperature is correlated with increased adult mortality from respiratory or cardiopulmonary disease, as well as deteriorated mental heath, lower firm productivity, and lower agricultural output (Chen, Chen, and Jintao 2016; Ebenstein et al. 2017; Shihe, Brian Viard, and Zhang 2021; Zhang, Chen, and Zhang 2018; Zhang, Zhang, and Chen 2017). Approximately 90% of these emissions come from coal-fired electricity generators (US Environmental Protection Agency 2005). In summary, air pollution and climate change have caused enormous health cost and social costs in China.

China's government has implemented a series of specific policies both in command-and -control and market-based policies to combat pollution and climate change. China has mainly relied on 'command-and-control' styled environmental regulations in the past two decades. In every five-year plan or special event, central government relied on shutting down manufacturing firms as a short-term solution. It seems to be costly to mitigate pollution and researchers keep on questioning the reasonability of this regulation (Chen, Oliva, and Zhang 2018; Guojun, Wang, and Zhang 2020; Kahn, Pei, and Zhao 2015). For example, in 2007, the central government launched an energy conservation and emissions reduction program that set mandatory targets for energy intensity (energy consumption per unit of GDP) for manufacturing firms. However, research shows that there are pollution transfers within the same conglomerate (Chen et al. 2021). On the other hand, China has emphasized the efficiency gains associated with market-based environmental policies. The central government tried to use tax or cap-and-trade policy instruments to correct environmental externality. Since 2000, China has implemented several SO2 emission trading pilots. In 2013, China started the regional seven carbon emission trading pilots in response to the climate change. At the beginning of 2018, China has implemented environmental tax nationwide. The large-scale shift away from the more traditional, more prescriptive 'command-and-control' approaches for regulating stationary point sources of pollution toward market-based approaches (such as pollution tax and cap-and-trade programs) has largely been justified on these grounds.

Another main characteristic of China's environmental regulation is that many existing regulations and standards are applied uniformly across firms at the national or industry level. For instance, environmental taxes are imposed on all firms, although provincial governments possess the authority to adjust the tax rates as they see fit. Additionally, tradable markets, such as the China Carbon Trading Market, rely on industry-level emission standards. However, the efficacy of such regulatory approaches in addressing environmental challenges remains a subject of contention among researchers and policymakers. Specifically, the extent of heterogeneity among producers in terms of air pollutants and CO2 remains inadequately understood. It is arguable that firms operating within the same industry may exhibit significant disparities in their pollution emissions. As a result, industry-level regulations could prove excessively stringent for some firms, while being overly lenient for others. This raises concerns about the economic efficiency of current environmental regulations in China, as it is likely that their effectiveness may be compromised in the face of such variability among firms within an industry.

In the context of China's ambitious goals to address environmental degradation and climate change, the manufacturing sector has consistently emerged as a key area of focus for government regulation. This emphasis can be attributed to the dominant role of the industrial sector in the Chinese economy and its significant contribution to air pollution and carbon dioxide emissions. China's rapid industrialization over the past few decades has resulted in the establishment of numerous manufacturing firms, ranging from heavy industries such as steel and cement to light industries such as textiles and electronics. Moreover, the manufacturing industry is a major source of air pollution and carbon dioxide emissions in China. The combustion of fossil fuels in manufacturing processes, coupled with the inadequate enforcement of environmental regulations and technological limitations, has resulted in the largest share of CO2 emissions from the industrial sector. To this end, the Chinese government has implemented a range of environmental regulations targeting the manufacturing sector, including emission standards, energy conservation measures, and pollution control policies. These measures aim to curb pollution and reduce carbon emissions by imposing stricter emission limits, promoting cleaner production technologies, and strengthening enforcement and compliance mechanisms.

China has put efforts into market-based environmental policies on manufacturing firms. There remains debate about whether these environmental regulation targets have substantially induced emission reduction in a least cost way has been a hot topic. There is always a question that what is the reasonable pollution/ carbon tax and what is the true mitigation cost for CO2? Does the carbon price reflect the true mitigation cost of firms? This paper tries to solve this problem by quantifying the productivity and distribution marginal abatement costs for CO2 for manufacturing firms.

2.2. EU carbon border adjustment mechanism

2.2.1. Legislative process

The EU carbon border tax has gone through a long process from proposal to legislative agenda. The carbon border tax was first proposed at the United Nations Climate Change Conference held in Nairobi in 2006 by French Prime Minister Dominique de Villepin. He suggested imposing additional tariffs on industrial products exported by countries that had not signed the Kyoto Protocol. Since then, there have been ongoing debates within the EU regarding the carbon border tax. Supporters hope to protect Europe's decarbonization achievements and avoid 'carbon leakage' by implementing a carbon border tax, while opponents are concerned that trade retaliation resulting from such a tax would outweigh its benefits and view it as a new form of 'ecological imperialism'. In 2017, Trump's announcement of US withdrawal from the Paris Agreement further increased the pressure on the EU to reduce emissions, prompting France to once again advocate for implementing a carbon border tax. In 2019, EU members reached a basic consensus on the issue of carbon border taxes and in December of that year, the EU issued its Green Deal policy document which formally proposed a 'Carbon Border Adjustment Mechanism' (CBAM) for the first time. In September 2020, European Commission President Ursula von der Leyen officially proposed legislation for CBAM to be included in the legislative agenda for 2021.

In March 2021, European Parliament passed a resolution on CBAM and in July of that year, the European Commission officially announced its proposal. On 22 March 2022, CBAM was approved at an Economic and Financial Affairs Council meeting of the European Union Council. On May, the Committee on Environment Public Health and Food Safety (ENVI) of European Parliament passed CBAM proposal. On 22 June, European Parliament finally reached an agreement within itself about whether or not to impose a Carbon Border Tax. The content includes that during the transition period between years from 2023 to 2026, the Carbon Border Tax will enter into force, and it will be officially implemented starting from year 2027. On 13 December, European Parliament reached a temporary agreement with the European Union Council, to establish CBAM, which will take effect from 1 October 2023. In 9 February, Committee on Environment, Public Health and Food Safety of the European Parliament formally passed the CBAM agreement with 63 votes in favor and 7 against, and further clarified the specific effective date is 1 October 2023. This means that world's first 'carbon tariff' mechanism is about to enter the implementation phase.

2.2.2. The key contents of carbon border tax

In the draft amendment to establish a carbon border adjustment mechanism passed by the European Parliament in June 2022, the official implementation date of the carbon tariff is set for 2027, with a transition period from 2023 to 2026. From a timeline perspective, during the transition period, companies in industries covered by the carbon border mechanism only need to fulfill reporting obligations without paying corresponding fees. They must report information on imported products, including import volume, country of origin, carbon emissions contained in products as well as indirect emissions and carbon prices paid for products in their countries of origin. In 2027, the EU will officially impose a 'carbon tariff'. Steel, cement, electricity, fertilizers, aluminum, and hydrogen gas, as well as indirect emissions and downstream products under specific circumstances will be among the first batch of industries included in this scope. By 2030 it is expected that all goods covered by the EU's carbon market will be subject to taxation, while free quotas allocated under the EU's Carbon Market will be reduced starting from 2026 until they are completely eliminated by 2034. The European Commission will mainly be responsible for implementing and supervising CBAM.

At present, the EU CBAM applies to five industries: cement, electricity, fertilizers, steel, and aluminum. The European Commission, the Council of the European Union, and the European Parliament are still in communication regarding the EU CBAM mechanism. It has not been ruled out that the scope of the collection may be expanded in the future. The revised draft currently includes carbon tariffs on electricity, all steel products, some steel products, some aluminum products, cement products, fertilizer-related products, organic chemicals, plastics, hydrogen, and ammonia. By 2030, all sectors covered by EU-ETS will be included in CBAM with priority given to goods most at risk of carbon leakage or those where production is most carbon-intensive. After a transitional period, importers will need to pay for emissions associated with their imported goods while considering whether to expand industry coverage. Currently, only relatively primary raw materials made into finished goods are included; more integrated products such as automobiles have not been involved.

In the CBAM bill, direct emissions are defined as 'emissions from goods directly controlled by producers in the production process'; indirect emissions refer to 'emissions caused by electricity generation, heating and cooling consumed in the production process of goods'. The amendment includes both direct and indirect emissions in its accounting scope. This means that in addition to direct emissions from product manufacturing, emissions generated by purchased electricity and heat used by manufacturers will also be included in carbon emission accounting. CBAM will cover steel, cement, aluminum, fertilizer and electricity, according to proposals from the Commission, as well as expanding to hydrogen, certain types of indirect emissions under specific conditions, some precursors and downstream products such as screws and bolts made of iron or steel. The new agreement expands inclusion of hydrogen (many EU countries include green hydrogen as a major decarbonization fuel, while non-EU countries mainly produce gray hydrogen using coal), several chemical precursors, some downstream products of steel (such as screws and bolts), and category two indirect emissions under specific conditions. The calculation method for CO2 is in Appendix: Calculating CO2 method.

The amendment points out that during the transition period from 2023 to 2026, for products exported to the European Union, free carbon emission quotas will be 100%.

Table 1. EU free carbon allowance withdrawal timetable.

year	2023–2026	2027	2028	2029	2030	2031	2032
Share of Free Quotas	100%	93%	84%	69%	50%	25%	0%

From 2027 onwards, free quotas will gradually decrease and be completely eliminated by 2032. The specific quota exit plan is shown in Table 1. At the same time, in order to ensure the effectiveness of the carbon market, while implementing a carbon border adjustment mechanism externally, the EU will also gradually reduce and eventually eliminate free carbon market quotas internally. The latest revised version stipulates that free quotas under EU-ETS will decrease synchronously until they are completely phased out by 2032.

Although the implementation of the EU CBAM is already a done deal, controversies surrounding carbon tariffs have never ceased internationally. The core of the controversy focuses on whether CBAM violates WTO principles and undermines the multilateral trading system. China has clearly expressed its opposition to CBAM, and countries such as India, Russia, and Brazil have also expressed concerns and criticisms about EU CBAM, believing that it is discriminatory and unfair, violates relevant rules on free trade, and is a dangerous trade barrier behavior. However, the EU has always insisted that CBAM is essentially compatible with WTO principles and hopes to promote climate-ambitious policies globally through carbon pricing and compliance. Exceptions in tariffs under GATT related to 'measures necessary for protecting human or animal life or health' and 'measures relating to conservation of exhaustible natural resources' are believed by outsiders to be clauses most likely used by the EU in resolving disputes between CBAMs.

3. Estimation strategy

3.1. Marginal abatement cost curve and shadow price

Previous research on MACC falls into three broad categories in terms of modeling approach, including the expert-based MACC, model-based MACC, and production-based MACC (Limin, Hanley, and Wei 2015). The production-based Marginal Abatement Cost Curve (MACC) stands out among other approaches, due to its solid foundation in production theory and its straightforward interpretation. This approach is characterized by its transparency, allowing us to easily appreciate the entirety of the underlying model. Another notable feature of this approach is the use of panel data, which enables us to capture sector characteristics and time trends. In addition, we provide a range of functional forms for the MAC curve, and carefully select the optimal one through rigorous evaluation using both in-sample fitting criteria and out-of-sample criteria. This is in contrast to previous studies that typically offer only one functional form option. As a result, our approach boasts several advantages, including its improved methodology and wider range of options for functional forms, which represent advancements over previous studies.

The shadow price of pollutants can provide an important price signal for carbon taxes related to pollutants and is also a powerful tool for policy-makers to evaluate whether environmental regulations have achieved economic efficiency. This study estimates CO2 shadow price for manufacturing firms across the years to depict industry-specific CO2 marginal abatement cost curves during the period. By comparing industry-specific marginal costs with levels of potential carbon pricing, we can simulate whether manufacturing firms would be affected under different scenarios of carbon pricing mechanism, including China National Carbon market and EU's planned implementation of carbon tariffs; whether some firms with outdated emission-reducing technologies would exit markets; if so, how much industrial output value it would cause.

To address these issues, we employ the shadow price approach based on directional distance function and representative firm survey data to calculate manufacturing firms' CO2 shadow price and draw up industry-specific marginal abatement cost curves. The dataset used is reliable and extensively covering various industries, which make our analysis a valuable reference material for policymakers regarding future carbon pricing policies.

The shadow pricing literature and technical efficiency literature provide a variety of methods to estimate the shadow price of environmental pollutants. Following Färe et al. (2005) and related literature afterward, we employ a parametric directional output distance function that is twice differentiable to derive estimates of elasticities of CO2. We also provide heterogeneity analysis across different sectors.

3.2. Directional distance function

The model used in this article refers to Fare et al. (2017) and their stochastic frontier approach for calculating the shadow price of pollutants. Let $x = (x_1, \ldots, x_n) \in R_N^+$ be the vectors for inputs, $b = (b_1, \ldots, b_J) \in R_J^+$ be the undesirable outputs, and $y = \left(y_1, \ldots, y_m\right) \in R_M^+$ be the desirable outputs, respectively. Assuming that each firm uses N input factors to produce desirable output y and undesirable output b, the environmental production technology is:

$$P(x) = \{(x, y, b) : xcanproduce(y, b)\}$$

Here are some assumptions:

We assume that good and bad outputs are null-joint; a firm cannot produce desirable outputs without producing undesirable outputs:

$$(y, b) \in P(x); b = 0theny = 0$$

We also assume weak disposability which means that the pollutant should not be considered freely disposable:

$$(y, b) \in P(x)and0 \leq \theta \leq 1, then(\beta y, \beta b) \in P(x)$$

According to the null-joint hypothesis and weak disposability, the directional distance function for firm k can be computed by solving the following optimization problem:

$$\vec{D}\left(x, y, b; g_y, -g_b\right) = \max\left\{\theta : \left(y + \theta g_y, b - \theta g_b\right) \in P(x)\right\}$$

Due to the translational property of directional distance function, it means that if both desirable and undesirable outputs increase byag_yor decrease by ag_b, the value of directional distance function will decrease by a (a scalar).

$$\vec{D}(x, y + ag_y, b - ag_b; g_y, -g_b) = \vec{D}(x, y, b; g_y, -g_b) - a$$

Then we parameterize the directional distance function in the form of a quadratic form:

$$\vec{D}_o(x, y, b; 1, 1) = \alpha_o + \sum_{n=1}^{3} \alpha_n x_n + \frac{1}{2} \sum_{n=1}^{3} \sum_{n'=1}^{3} \alpha_{nn'} x_n x_{n'} + \beta_1 y_1 + \frac{1}{2}\beta_{11} y_1^2 + \sum_{j=1}^{2} \gamma_j b_j + \frac{1}{2} \sum_{j=1}^{2} \sum_{j'=1}^{2} \gamma_{ijb_j b_{j'}} + \sum_{n=1}^{3} \delta_{n1} x_n y_1 + \sum_{n=1}^{3} \sum_{=1}^{2} \eta_n x_n b + \sum_{=1}^{2} \mu_1 y_1 b_j$$

On this basis, add an error term. $v \sim N(0, \sigma_v^2)$, Estimate the equation using the method of random frontier. By utilizing the property of transformation, we have:

$$\vec{D}_o(x, y, b; 1, 1) - \alpha = \alpha_0 + \sum_{n=1}^{3} \alpha_n x_n + \tfrac{1}{2} \sum_{n=1}^{3} \sum_{n'=1}^{3} \alpha_{nn'} x_n x_{n'} + \beta_1 (y_1 + \alpha) + \tfrac{1}{2}\beta_{11}(y_1 + \alpha)^2 + \sum_{j=1}^{2} \gamma_j (b_j - \alpha) + \tfrac{1}{2} \sum_{j=1}^{2} \sum_{j'=1}^{2} \gamma_{ij'} (b_j - \alpha)(b_{j'} - \alpha) + \sum_{n=1}^{3} \delta_{n1} x_n (y_1 + \alpha) + \sum_{n=1}^{3} \sum_{j=1}^{2} \eta_{nj} x_n (b_j - \alpha) + \sum_{j=1}^{2} \mu_{1j} (y_1 + \alpha)(b_j - \alpha) + v$$

Subtract both sides at the same time $\vec{D}(x, y, b; 1, 1) = \mu$, which is the inefficient fraction, which yields

$$\begin{aligned} -\alpha = {} & \alpha_0 + \sum_{n=1}^{3} \alpha_n x_n + \frac{1}{2} \sum_{n=1}^{3} \sum_{n'=1}^{3} \alpha_{nn'} x_n x_{n'} + \beta_1 (y_1 + \alpha) + \frac{1}{2}\beta_{11}(y_1 + \alpha)^2 \\ & + \sum_{j=1}^{2} \gamma_j (b_j - \alpha) + \frac{1}{2} \sum_{j=1}^{2} \sum_{j'=1}^{2} \gamma_{jj} (b_j - \alpha)(b_{j'} - \alpha) \\ & + \sum_{n=1}^{3} \delta_{n1} x_n (y_1 + \alpha) + \sum_{n=1}^{3} \sum_{j=1}^{2} \eta_{nj} x_n (b_j - \alpha) \\ & + \sum_{j=1}^{2} \mu_{1j} (y_1 + \alpha)(b_j - \alpha) + v - \mu \end{aligned}$$

Here a represents the value of undesirable output. By using ML methods to estimate the above equation and obtaining estimated coefficients, these coefficients are then substituted into the formula for shadow prices.

$$q_i = -p_i \frac{\partial \vec{D}_i(x, y, b; g)/\partial b_i}{\partial \vec{D}_i(x, y, b; g)/\partial y_i}$$

Among them, q_i is the shadow price for undesirable output (pollutant) and the p_i is shadow price for desirable output (normal industrial outputs).

This study intends to use three inputs: capital, labor, and the amount of standard coal equivalent for various energy uses. The desirable output is industrial added value, while the undesirable output is carbon dioxide emissions calculated based on energy consumption. Therefore, the directional distance function of the quadratic form is:

$$\vec{D}(x, y, b; g) = \alpha_0 + \sum_{n=1}^{3} \alpha_n x_n + \beta_1 y_1 + \gamma_1 b_1 + \tfrac{1}{2} \sum_{n=1}^{3} \sum_{n'=1}^{3} \alpha_{n,n'} x_n x_{n'} + \tfrac{1}{2}\beta_{11} y_1^2 + \tfrac{1}{2}\gamma_{11} b_1^2 + \sum_{n=1}^{3} \delta_{n1} x_n y_1 + \sum_{n=1}^{3} \eta_{n1} x_n b_1 + \mu_{11} y_1 b_1 + v - u$$

By using transformation, we can obtain:

$$-b_1 = \alpha_0 + \sum_{n=1}^{3} \alpha_n x_n + \beta_1 (y_1 + b_1) + \frac{1}{2} \sum_{n=1}^{3} \sum_{n'=1}^{3} \alpha_{n,n'} x_n x_{n'} + \frac{1}{2} \beta_{11} (y_1 + b_1)^2 + \sum_{n=1}^{3} \delta_{n1} x_n (y_1 + b_1) + v - u$$

Using ML to estimate the coefficients in the above equation and plugging them into the shadow price formula, we obtain the shadow prices of undesirable output:

$$q_i = -p_i \frac{\gamma_1 + \gamma_{11} b_1 + \sum_{n=1}^{3} \eta_{n1} x_n + \mu_{11} y_1}{\beta_1 + \beta_{11} y_1 + \sum_{n=1}^{3} \delta_{n1} x_n + \mu_{11} b_1}$$

4. Data and variables

This study utilizes an administrative enterprise tax dataset obtained from the Chinese State Administration of Tax (SAT), which serves as the central authority responsible for tax collection, auditing, and supervision of various tax assistance programs. Leveraging this rich administrative data source, we are able to construct detailed firm-level information for individual manufacturing firms for the period 2011–2015. The administrative records maintained by the SAT contain both tax payment records and financial statement information, as well as detailed energy usage information, which are instrumental in calculating carbon emissions.

According to the shadow price model, the *industrial value added* of the firms in that year is desirable output. Firms' outputs are mainly represented by three variables: total industrial output value, industrial sales revenue, and industrial value added. Among them, industrial value added is only related to the three input factors of fixed capital, labor force, and land. It is the output indicator closest to the actual creation of wealth by firms. If this indicator is missing in the original data, then industrial value added will be calculated based on 'product sales – beginning inventory + ending inventory – intermediate inputs + value-added tax'. Labor, capital, and energy usage are selected as inputs. In this study, the *annual net value of fixed assets* is selected as the proxy indicator for the capital. If this indicator is not available in the database, then estimation will be made using the formula 'Net Value of Fixed Assets = Original Value of Fixed Assets – Accumulated Depreciation'; For labor input indicators, annual number of employees is chosen as a proxy indicator for labor. Due to data limitations, no distinction is made regarding labor quality; for energy input, all types of energy are converted into standard coal consumption.

Carbon dioxide generated by burning fossil fuels is chosen to represent undesirable outputs produced by a firm. In this study, based on the energy consumption in the original data and referring to various emission factors provided by IPCC, carbon dioxide emissions are calculated. Our study mainly refers to benchmark methods provided in the Energy section under '2006 IPCC Guidelines for National Greenhouse Gas Inventories'. The calculation formula for carbon dioxide emissions caused by consuming fossil fuels can be expressed below:

$$CO_2 = \sum_{i=1}^{6} E_i \times CF_i \times CC_i \times COF_i \times (44/12)$$

where i represents an index of different types of fossil fuels. We consider the consumption of seven different primary fuel types, i.e. coal, coke, gasoline, kerosene, diesel, fuel oil, and natural gas. The term 44/12 is the ratio of the mass of one carbon atom when combined with two oxygen atoms to the mass of an oxygen atom. The variables E_i, CF_i, CC_i and COF_i represent the total consumption, the relevant transformation factor, the carbon content, and the carbon oxidation factor of fuel i, respectively.

In this study, the energy used by firms is first converted into standard coal, and then multiplied by the carbon dioxide emission factor of standard coal to calculate carbon dioxide emissions. The calculated carbon emissions are the energy end-consumption carbon emissions from fossil energy consumption, excluding carbon emissions from secondary energy consumption. This study will consider the carbon dioxide emissions corresponding to all fossil energy sources in Appendix Table A1.

Although this method only considers the carbon emissions from fuel use and cannot take into account the emission during raw material use, for most highly polluting industries, the proportion of carbon emissions generated during raw material or other processing processes is relatively small, while those generated during energy utilization process are largest. Therefore, using fossil fuel consumption to calculate the carbon emissions of heavily polluting enterprises is more reasonable.

After selecting the indicators, follow the standard process to clean up the data: (1) remove companies with missing key financial indicators; (2) remove firms with completely missing key energy usage data; (3) remove firms that obviously do not comply with accounting standards, finally, we conduct 1% winsorize on all variables and retain firms that existed in 2011, 2012, 2013, 2014, and 2015 to construct a balanced panel. Considering that the linear programming requires as many firms as possible in each period to avoid insufficient observations for solving the production frontier, this study retains industries with at least 50 firms per year, resulting in a total of 9416 firms per year and a total of 47,080 observations in 5 years. Additionally, each firm's belonged industry classification is identified according to National Economic Industry Classification Standards (GB T4754–2011), and whether a firm is an export firm was identified based on its export volume (>0). Descriptive statistical information can be found in Appendix Table A2. The final variable, 'Whether it is an export enterprise,' is a binary variable representing whether the enterprise is engaged in export activities. It has a mean of 0.54, indicating that slightly more than half of the enterprises in the sample are export enterprises. The standard deviation is 0.498, reflecting a relatively balanced distribution between export and non-export enterprises.

5. Results

Utilizing the shadow price model as introduced hereinabove, we use Stata software to derive the parameters of the directional distance function. It is worth noting that in the feasible set of environmental production technology, the production of desirable and undesirable outputs occurs jointly, with no scenario where solely desirable output can be produced. Consequently, a subset of firms within the sample cannot acquire their CO2 shadow prices, as indicated by negative directional distance function values, leading to missing model operation results. To facilitate comparability of shadow prices across different years, the study purges the data of firms that remain unsolvable.

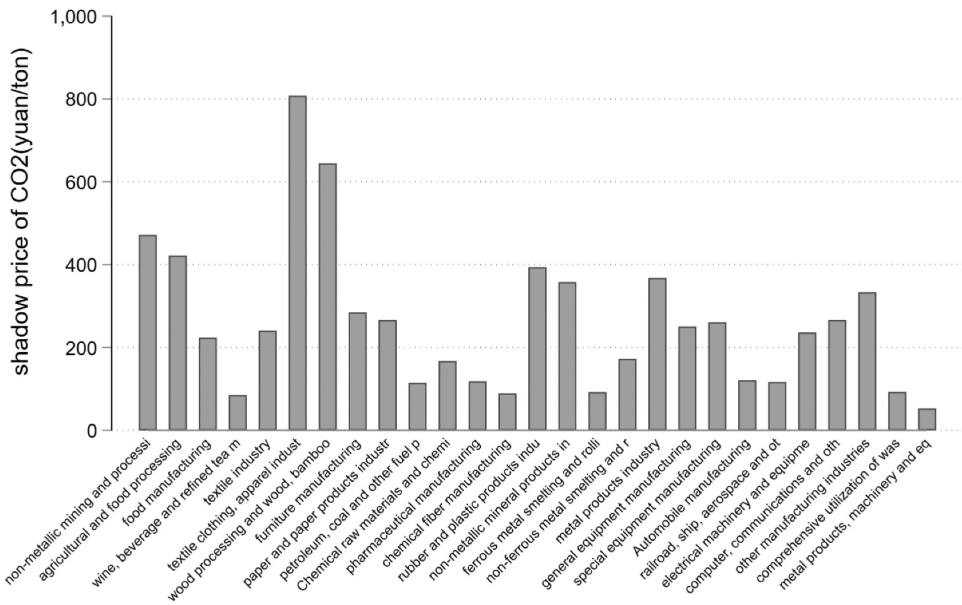

Figure 1. Average CO_2 shadow prices for all industries in the sample (yuan/ton).

Thus, this study yields industry- and year-specific parameters of the directional distance function, enabling the computation of CO2 shadow price for firms included in the sample. The main findings of the analysis are as follows: we provide the shadow price estimation and the time-series trend for shadow price of CO2 for Chinese manufacturing firms. Then, we explore the indicators influencing the shadow price. Finally, we provide the simulation of the cost of China's CO2 emission-reduction strategy.

5.1. By industry

Figure 1 reveals that the CO2 shadow prices of various conventional polluting industries exhibit a relatively high level, notably the chemical, nonmetallic, black metal, non-ferrous metal, and metal products sectors (see Appendix Table A3 and A4 for the classification of polluting industry and distribution of sample firms). This pattern indicates a substantial reliance on carbon-intensive production methods within these industries, implying a higher cost of pollution abatement. Moreover, it underscores the need for firms operating in these sectors to undertake environmentally sustainable production practices to mitigate their carbon footprint.

Notably, machinery manufacturing industries, including general equipment manufacturing, automobile manufacturing, and electrical machinery, also demonstrate high CO2 shadow prices. These findings suggest that the production of machinery involves significant carbon emissions, thereby creating a significant externality, as firms are not typically held accountable for the environmental costs of their production. The high shadow prices observed in these industries signify the potential benefits of carbon taxation policies, which can serve to internalize the externalities associated with carbon emissions and incentivize firms to adopt more sustainable production methods.

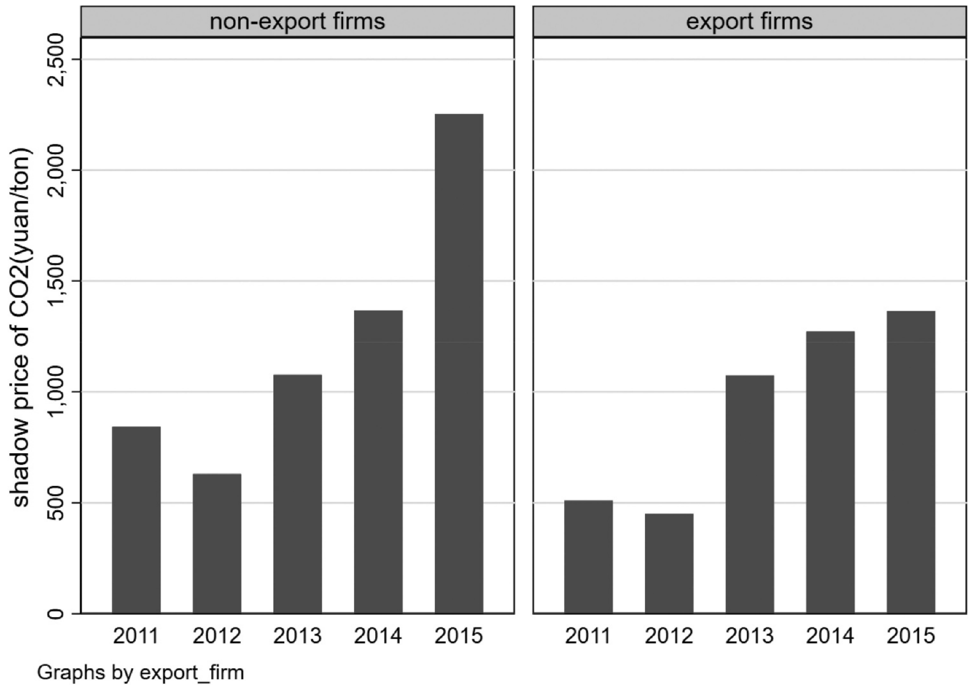

Figure 2. Average CO_2 shadow prices for ex porting and non-exporting industries(yuan/ton).

Overall, it may be unsurprising that shadow prices vary so much, since differences in fuel inputs and variation across mitigation technologies are important. The identification of industries with high CO2 shadow prices highlights the need for proactive measures to mitigate the negative externalities associated with carbon emissions. Policymakers can leverage this information to design and implement effective carbon pricing schemes, which can promote sustainable development and environmental protection while ensuring economic growth and competitiveness.

5.2. Time series trend

The analysis of annual changes in the shadow price of carbon dioxide for industrial firms in the sample (shown in Figure 2) reveals a significant increase from 2012 to 2015, with export firms registering an almost three-fold growth. This pattern is consistent with the increasing emphasis on environmental protection efforts by the central government during the sample period. The Chinese government first called for ‘energy conservation and emission reduction’ in 2007, followed by the initiation of carbon trading pilots in five provinces and two cities in 2013, signaling a growing focus on policy measures to address climate change. The significant rise in CO2 shadow prices signifies an increased economic output value that firms must forego to reduce each unit of pollutant emissions, indicating that China’s industrial firms face rising marginal costs for CO2 emissions.

The estimation results of this study for carbon dioxide shadow prices are notably higher than those of previous research conducted using provincial or industry-level data. This finding highlights the importance of using more detailed firm-level data for

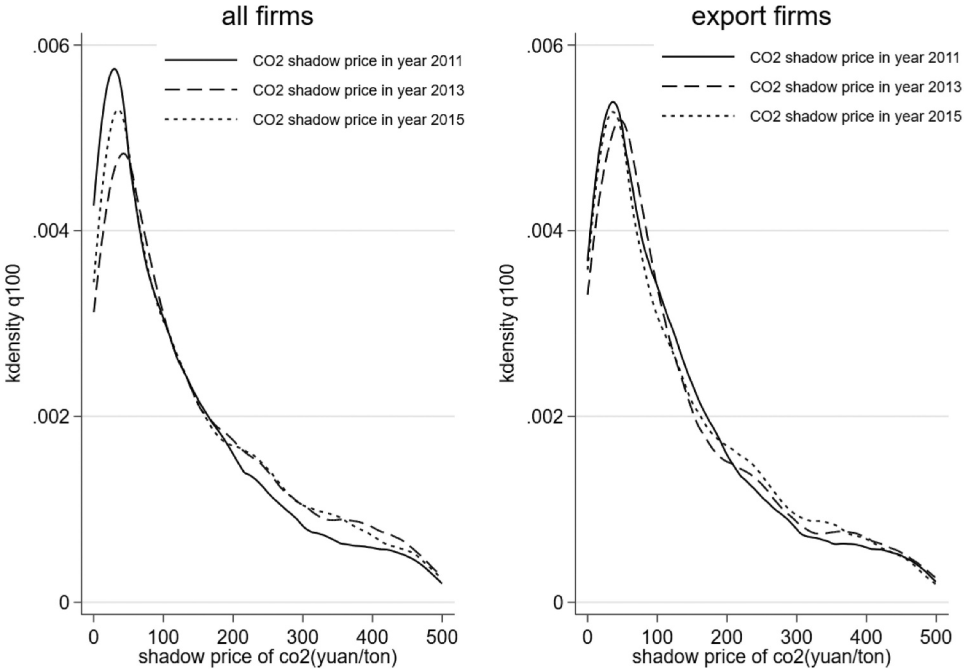

Figure 3. Kdensity distribution of shadow price of carbon dioxide (CO_2) for sample enterprises.

reliable and accurate estimations of CO2 shadow prices, as they capture the heterogeneity in production processes and technology choices across firms. Moreover, the high shadow prices obtained in this study demonstrate the potential benefits of implementing carbon pricing policies, which can help to internalize the negative externalities of carbon emissions and incentivize firms to adopt cleaner production methods.

The kdensity distribution of three types of pollutant shadow prices for sample companies in 2011, 2013, and 2015, as shown in Figure 3, provides valuable insights into the trends of environmental protection efforts by Chinese firms during the sample period. From the figure, it is evident that from 2011 to 2015, both export and non-export sample firms' CO2 shadow prices have gradually increased, indicating a positive shift toward more environmentally sustainable practices. In 2011, the shadow prices deviate from about 50 Yuan/t to 150 Yuan/t with the majority of the estimates clustering around the 100 Yuan/t mark. The kernel density curve shifts significantly to the right by 2013, exhibiting a wider dispersion range and a lower clustering point.

The kdensity distribution curve of CO2 shadow prices shifted to the right in 2015, indicating that compared with 2011, the average CO2 shadow price of sample companies has increased. Theoretically speaking, as environmental regulations become increasingly stringent and firms' output expands, the opportunity cost for reducing each additional unit of CO2 will become higher and higher for firms. In practice, from 2011 to 2015 China's policies on environmental governance and climate change response have become increasingly stronger which corresponds to an increasing trend in marginal abatement costs shown in Figure.

However, it is important to note that the concentration of shadow prices was significantly lower in 2015 than it was in 2011. This trend in changes in shadow price distribution represents the degree of convergence in emission reduction costs among enterprises within the industry. The lower the concentration of shadow prices, the greater the difference between marginal emission reduction costs among enterprises. The policy implication of this phenomenon is that current climate policies do not influence enterprise's emission reduction behavior through economically efficient means. Even if there is progress made toward reducing emissions, it comes with higher social costs. This inefficient policy may have some short-term effects but due to its high cost and lack of cooperation willingness from local governments and businesses, it can lead to repeated fluctuations in emission reductions and fail to establish a long-term governance mechanism. To achieve minimal total social cost for environmental policies aimed at reducing emissions across all industries, emission reduction policies should result in convergence and similarity among pollutant shadow prices (i.e. marginal abatement costs) for all companies within an industry. If there are large differences between marginal abatement costs among companies, then effective economic measures have not been implemented which is a common characteristic when administrative forces drive emissions reductions because only economic measures can converge marginal abatement costs thereby achieving minimal total social cost (Coggins and Swinton 1996; Xu et al. 2010).

In this study, we have analyzed the annual changes in shadow prices over a sample period from 2011 to 2015. Our findings indicate that industrial enterprises faced increasing environmental regulations during this period, resulting in an increase in marginal abatement costs for carbon dioxide. However, the policies adopted during this period were not truly market-oriented, leading to significant efficiency losses for industrial enterprises in terms of resource allocation. These losses have gradually expanded over time.

The failure of non-market-oriented policies to incentivize efficient resource allocation is a well-established result in environmental economics (Stavins 2011; Goulder and Stavins 2011). In contrast, market-based policies such as carbon pricing, cap and trade systems, and emissions taxes have been found to promote cost-effective abatement strategies and encourage innovation in clean technologies (Pizer 2002; Aldy and Stavins 2012). In light of these findings, it is imperative for policymakers to consider market-based mechanisms to achieve optimal environmental outcomes. This includes designing carbon pricing mechanisms that reflect the true social cost of carbon emissions and fostering innovation in clean technologies through supportive policies such as research and development funding and technology transfer initiatives. By doing so, policymakers can promote cost-effective abatement strategies and encourage innovation in clean technologies, while minimizing the efficiency losses that can arise from non-market-oriented environmental policies.

5.3. Compared to other results of CO2 shadow pricing

We aim to provide a comprehensive comparison and analysis of its results with the existing literature on China's carbon dioxide shadow prices. This analysis is based on a comparison with relevant studies that used both directional distance function and linear programming models. As Table 2 illustrates, there are significant differences in the estimation of carbon dioxide shadow prices across various studies conducted in China, ranging from 50 yuan/ton

Table 2. Summary of calculated shadow prices for carbon dioxide in China.

Article	Time Interval	Decision Maker (DMU)	Method	Shadow Price Result
Wang et al. 2011	2007	28 provinces in China	DDF/DEA	475.3 yuan/ton
Wei et al. 2012	1995–2007	29 provinces in China	DDF/SBM-DEA	139.5 yuan/ton(2002)
Choi et al. 2012	2001–2010	30 provinces in China	DDF/SBM-DEA	49.54yuan/ton
Lee and Zhang, 2012	2009	38 industrial sectors in China	TDDF/N	28.31yuan/ton
Peng et al. 2012	2004,2008	24 industrial sectors in China	DDF/DEA	200yuan/ton
Wei et al. 2013	2004	124 thermal power companies in China	QDDF/N	2059.8 yuan/ton
Chen 2013	1980–2010	30 industrial sectors in China	DEA/N	2731 yuan/ton
Zhang et al. 2014	2006–2010	30 provinces in China	QDDF	22.42 yuan/ton(2006)
Zhou et al. 2015	2009–2011	Shanghai industrial sector	QDDF/TDDP/N/P	394.5–1906.1 yuan/ton
Limin et al. 2015	2001–2010	30 provinces in China	QDDF/N	2100 yuan/ton(2010)
Du et al. 2016	2008	648 thermal power companies in China	QDDF/N	1663.13yuan/ton
Tang et al. 2016	2003–2012	30 provinces in China	QDDF/N	5512 yuan/ton
Wang et al. 2016	1996–2012	30 provinces in China	DDF/N	3000 yuan/ton(2005);
Wang et al. 2017	2014	49 steel companies in China	ODDF/P	1226yuan/ton

1. TDDF: Translog directional distance functional form; QDDF: Quadratic directional distance functional form; ODDF: Output directional distance function; P: Parametric; N: Nonparametric; SBM-DEA: Slack-based measure Data envelope analyses）; 2.Due to the fact that previous studies in the 1990s generally used transcendental distance functions, which failed to distinguish between desirable and undesirable outputs, so no comparison is made here.

to 5000 yuan/ton. In this study, the estimated carbon dioxide shadow price using a directional distance function approach is approximately 379 yuan/ton (2012 result), which falls between the estimates of two provincial-level studies by Wang et al. (2011) and Wei et al. (2012). The differences in results may be due to the adoption of different methodological approaches. Wei et al. (2012) used a non-parametric method, which may have contributed to the divergence in the estimated shadow prices.

Furthermore, this study's average shadow price of CO2 is lower than that estimated by Wei et al. (2015) and Wang et al. (2017), who used data from thermal power plants and steel enterprises, respectively. However, the present study found that some state-owned large-scale thermal power plants and steel enterprises in the sample had shadow prices that exceeded the industry average. It is possible that Wei et al. (2015) and Wang et al. (2017) obtained data mainly from these large enterprises, resulting in the high estimates of carbon dioxide shadow prices. Therefore, it is crucial to consider the representativeness of the sample when estimating pollutant shadow prices.

To achieve better comparability and consistency in the estimation of pollutant shadow prices, future research should adopt standardized methods and datasets that account for variations in industry structure and geographical regions. Additionally, policymakers need to provide more accurate and timely data on carbon emissions and related costs, which can help to establish a comprehensive and effective framework for environmental policy. The findings of this study highlight the importance of developing evidence-based environmental policies that can achieve emission reduction targets at minimal social cost.

5.4. Simulations: MAC and optimal tax rate

Currently, there exist three dominant methodologies for drawing marginal abatement cost curves. The first method, referred to as the emission reduction cost model based on engineering solutions or Expert-based MACC, is a bottom-up analytical approach that evaluates the emission reduction potential and cost of a single technology solution based on assumptions made by experts. The marginal abatement cost curve is then constructed by ranking all emission reduction technology solutions from low to high according to their costs. The second method is based on computable general equilibrium models (CGE), which involves constructing a local or general equilibrium model and modifying the model's constraints to obtain different marginal abatement cost information. For instance, reducing emissions to a certain level can yield different marginal abatement costs at different emission reduction levels. The third method is the micro-perspective marginal abatement cost model, which is the focus of this paper. This model defines the production possibility set and derives pollutant marginal abatement costs under given production technology and economic constraints. Generally, this model employs multi-input multi-output production models to describe the relationship between marginal abatement costs and emissions reductions. Given its empirical grounding and few theoretical assumptions, this method has found widespread use in estimating shadow prices of pollutants across various levels.

This study adopts a micro-perspective marginal abatement cost model to estimate industry-specific marginal abatement cost curves for carbon dioxide emissions. The basic procedures are as follows: (1) The study first estimates CO2 shadow prices for all firms in each industry using benchmark results. The firms are then sorted from high to low according to their shadow prices, and their CO2 emissions are cumulatively added one-by-one. (2) The total pollutant emissions of the industry can be obtained after adding up the CO2 emissions of all firms, and the corresponding shadow price is the lowest in the industry. (3) A horizontal axis representing the total emission volume for an industry is plotted, while the vertical axis represents the marginal abatement cost curve for CO2 shadow prices within that industry. (4) The study approximates the function form of the marginal abatement cost curve through numerical simulation of its values. (5) The full-industry CO2 emissions corresponding to various carbon tariff amounts are calculated under the assumption that, at the current level of technology, and assuming there have been no significant changes in CO2 reduction technologies across various enterprises, achieving the industry-wide CO2 reduction target can be done by eliminating the firms with the lowest shadow price of CO2. This method provides a comprehensive framework to evaluate the cost-effectiveness of CO2 reduction policies and can assist policymakers in developing efficient and effective strategies to mitigate CO2 emissions.

The industry-specific marginal abatement cost curves that have been drawn using the third research perspective in this study can provide valuable insights for policymakers in the context of carbon tariffs. By setting a carbon tariff at a certain level, policymakers can refer to the completed marginal abatement cost curve to identify the corresponding shadow price on the vertical axis. The total CO2 emissions of the industry can then be determined based on the horizontal axis, which represents the quantity of CO2 emissions that will remain in the industry at the given tariff level. Companies with emissions below this standard will exit the market, along with their production capacity. It should be noted that the shadow prices used to draw up the marginal abatement cost curves in this study are from 2015, as samples from 2022 were not available. Thus, the results should be interpreted with caution when applied to more recent data.

What impact will the EU's CBAM have on China? First of all, considering that China is both Europe's largest trading partner and its largest source country for imported goods

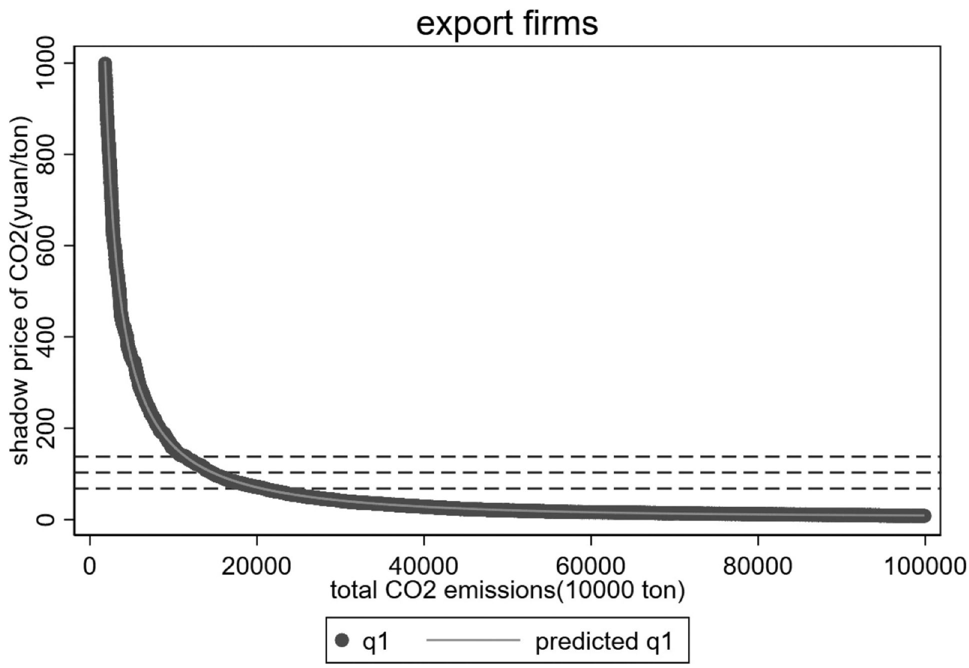

Figure 4. Marginal abatement cost curve of carbon dioxide for all sample export firms.

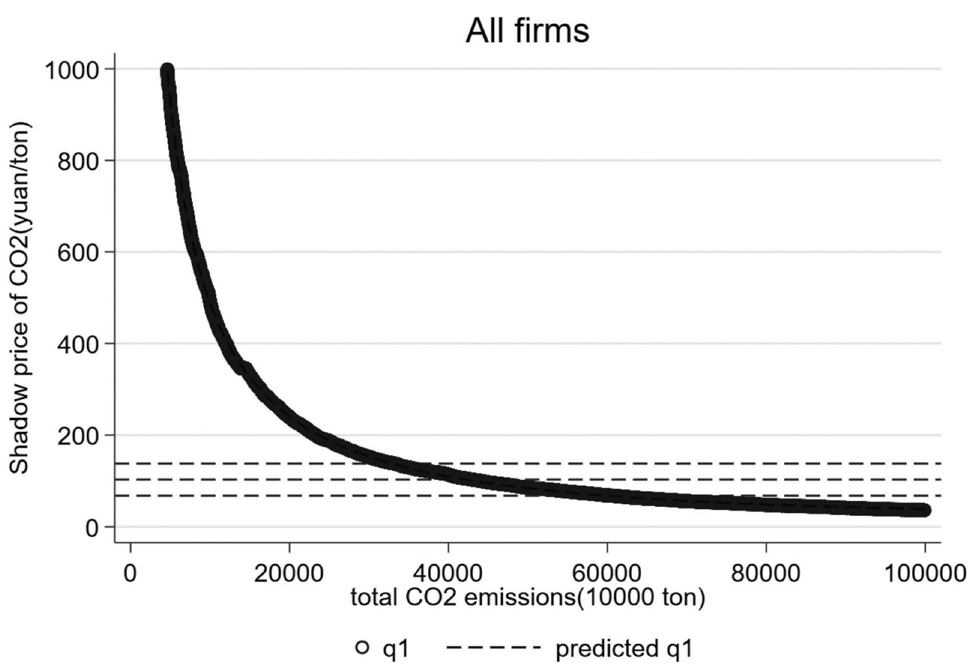

Figure 5. Marginal abatement cost curve for all sample firms in terms of carbon dioxide reduction.

with implicit carbon emissions from 80% of The Chinese exports being derived from high-leakage risk sectors such as metals, chemicals and nonmetallic minerals which fall within Europe's carbon market scope; once included in CBAMs this will inevitably have a huge impact on Chinese exports. There have been many studies conducted around how the EU's CBAM would affect trade. We take EU carbon tariff for an example to simulate policy outcome. As per the relevant EU policy documents, there are three potential scenarios for setting carbon tariffs: €50, €75, and €100. However, companies are not expected to bear the full burden of these taxes, and an elasticity rate of 20% is chosen to estimate the actual tax burdens, resulting in €10, €15, and €20, respectively (equivalent to RMB68 yuan, RMB103 yuan, and RMB138 yuan). The marginal abatement cost curves, shown in Figures 4 and 5, indicate that all firms, export and non-export alike, would experience a significant loss of industrial added value if these carbon tariffs are imposed. For all export firms, the corresponding loss of industrial added value is estimated to be ¥2513.89 billion, ¥3547.42 billion, and ¥4449.26 billion for the three carbon tariff levels, respectively. For all enterprises, the corresponding loss of industrial added value is estimated to be ¥4452.26 billion, ¥6304.31 billion, and ¥7833.10 billion, respectively. The losses for non-export firms are estimated to be ¥1938.37 billion, ¥2756.89 billion, and ¥3383.84 billion, respectively. As the shadow price for CO2 is lower for export firms compared to non-export firms, the former are expected to suffer greater losses.

6. Conclusions

This paper intends to derive shadow prices for CO2 using the most detailed firm-level data that cover the entire Chinese industrial sector. We provide the first estimates of within-industry heterogeneity in marginal abatement cost of CO2 for the entire Chinese industrial sector. Three findings emerge:

First, within narrowly defined industries, heterogeneity in CO2 shadow price across firms is enormous. Second, heterogeneity in CO2 shadow price exceeds heterogeneity in other firm characteristics, like labor or capital. Third, based on the marginal abatement cost curves, we simulate the potential impact of the upcoming EU CBAM on the output loss of the Chinese industrial sector. The results reveal that all firms, export-oriented and domestic firms export would encounter a substantial decline in industrial added value should these carbon tariffs be imposed.

This result provides several policy implications:

Firstly, policy-makers need to consider industrial and regional characteristics to develop effective policies that conserve energy and mitigate climate change. Therefore, it is crucial to establish effective policies that promote convergence of marginal abatement costs among companies within industries. This can be achieved through the implementation of economically efficient measures such as carbon pricing, cap-and-trade systems, and other market-based instruments. Additionally, government policies that incentivize firms to adopt cleaner technologies and encourage the adoption of sustainable practices can also contribute to the convergence of marginal abatement costs. Such policies should be designed to balance economic growth with environmental sustainability, recognizing that these two objectives are not mutually exclusive. By promoting the convergence of marginal abatement costs among companies within industries, it is possible to achieve minimal total social cost for environmental policies aimed at reducing emissions across all industries. Lessons are also valuable for other developing countries as some populated developing countries are experiencing much more severe air pollution than China.

Second, how should China respond to the EU's proposed policy? It is recommended that dialogue at political and technical levels be strengthened between both sides, so they can avoid adopting carbon taxes altogether. Secondly, domestic markets need further improvement so companies operating within industries facing potential pressure due to CMBAs can prepare themselves ahead of time. Thirdly, timely withdrawal from Carbon Taxes may be considered along with complementing existing domestic markets thereby promoting low-carbon development pathways whilst avoiding the imposition of additional taxes onto industries not yet covered under our own domestic market. Furthermore, it requires pushing enterprises toward implementing strategies aimed at achieving net-zero emissions. By guiding businesses toward accelerating their efforts toward net-zero emissions and developing appropriate reduction paths, this allows us greater flexibility when faced against future green-trade trends, thus avoiding any potential imposition of additional taxes due to higher CO2 emissions. In addition, the recognition given by Europeans regarding whether Chinese enterprise products meet net-zero standards depends entirely upon what criteria they choose alongside what standards are adopted. This further necessitates strengthening diplomatic ties between both parties

Disclosure statement

No potential conflict of interest was reported by the author(s).

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Appendix

Table A1. Standard coal conversion and CO_2 emission reference coefficients of various energy sources.

Industry	Standard Coal Conversion Coefficient(kgce/kg)	CO2 Emission Coefficient(kg-co2/kg)
Raw Coal	0.7143	1.9003
Coke	0.9714	2.8604
Crude Oil	1.4286	3.0202
Fuel Oil	1.4286	3.1705
Gasoline	1.4714	2.9251
Kerosene	1.4714	3.0179
Diesel Oil	1.4571	3.0959
Liquefied Petroleum Gas (LPG)	1.7143	3.1013
Refinery Dry Gas	1.5714	3.0119
Oilfield Natural Gas	1.3300	2.1622

Table A2. Descriptive statistics of the sample.

	Unit	Mean	SD	Min	Max
Labor force	People	439.982	558.714	1	2299
Capital	Ten Thousand Yuan (CNY)	93226.679	181781.54	0	781810
Energy consumption	Ton Standard Coal (TCE)	4686.825	14084.125	0	66032.761
Industrial added value	Ten Thousand Yuan (CNY)	60199.068	119200.12	−51278	466636
CO_2 emissions	Ton	9349.17	29003.111	0	149670.32
Whether it is an export enterprise	A one-digit export enterprise	.54	.498	0	1

Table A3. Polluting sectors (SO2 emission-intensive sectors).

Sector	SO2 share in total industrial SO2 emissions
Production and supply of electricity	50.4%
Non-Metallic Mineral Products	12.7%
Ferrous Metal Mining and Processing	10.4%
Chemical Products	6.1%
Non-Ferrous Metal Smelting	5.8%
Petroleum processing and coking	3.1%
Sum	88.5%

Data source: China Pollution Source Census 2007.

Table A4. Sector distribution of sample firms.

Sector name	Number of Firms
Non-polluting Sectors	
Beverage Manufacturing	236
Textiles Mills	940
Clothing and other fiber manufacturing	68
Pulp and paper	426
Petrochemicals	331
Chemical Fibers	62
Rubber and Plastic	205
Electrical machinery and equipment	49
Nonmetal Minerals Mining and Dressing	22
Ferrous-metal smelting and rolling	260
Non-Ferrous Metal Mining	31
Metal Products	204
Polluting Sectors	
Non-Metallic Mineral Products	590
Chemical Products	958
Ferrous Metal Mining and Processing	23
Petroleum processing and coking	132
Production and supply of electricity	71
Non-Ferrous Metal Smelting	163

Note: Industrial classification for national economic activities (GB/T 4754—2002). The division between polluting Industries and nonpolluting Industries is according to the Ministry of Environmental Protection (http://wfs.mep.gov.cn/gywrfz/hbhc/zcfg/201009/t20100914_194483.htm).

Calculating CO2 method

According to the amendment, the EU carbon border tax = (carbon emissions of exported products - EU free carbon quotas) × quantity of exported products × EU carbon price - carbon market payment fees paid by exporting countries. The amendment states that the Carbon Border Adjustment Mechanism needs to closely reflect the price of the EU-ETS and determine the price of CBAM certificates based on the average transaction price of quota auctions on the EU-ETS market calculated weekly.

The formula for calculating carbon dioxide emissions is as follows:

Carbon dioxide emissions from goods = Goods mass × Emission intensity of goods

Overall, the applicant needs to prove the actual emissions and emission intensity of imported goods in order to purchase vouchers based on those actual emissions. If the declared actual emission intensity cannot be verified (such as due to missing data), default emission intensities will be applied.

The amendment states that only actual values from countries with real emissions can be used to determine a product's inherent emissions. When the actual emission amount of exported products cannot be fully determined, the average emission intensity of the worst-performing 10% of each type of good exported by each exporting country should be used, and an additional markup should be added as a default value. When reliable data from exporting countries cannot apply to certain types of goods, default values should be based on the average emission intensity of the worst-performing 5% products in that category within the EU. In any case, default values must not fall below possible inherent emissions.

Carbon emission defaults should be determined based on best available data, which should rely on reliable and publicly available information and updated according to the latest and most reliable information. Reliable and public information includes technology and process types used, factory design, input materials used during production processes for simple commodities' sources energy usage among other factors while latest or most reliable information is revised periodically based on third-country or third-country group-provided information.