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Research article

Introducing a floor price in China's national carbon market

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ABSTRACT

The national carbon market serves as an essential policy tool for China to achieve the "dual carbon" goals. However, the current market is characterised by quota over-allocation and market prices disconnected from abatement costs. To inspire emissions reduction and low-carbon investment, this study suggests setting carbon floor prices complementary to the benchmark approach in China's national carbon market. Based on 30 Chinese provinces data, the equivalent marginal abatement costs are estimated by a quantile parametric directional output distance function method, and the suggested carbon floor price for each of the years 2021–2024 is CN¥59.68/tCO_2, CN¥61.17/tCO_2, CN¥62.95/tCO_2, and CN¥64.21/tCO_2, respectively. The need for and feasibility of a floor price instrument are verified by comparing market prices and carbon costs embodied in green electricity prices. Furthermore, concerned about its potential cost-push effects, we simulate the short-term effects of a floor price using a non-competitive input-output price model. The results show that a floor price would not only lead to a cost-push effect in the covered power sector but also would have a more indirect influence on non-covered sectors with higher emissions, while the overall impacts of the floor price on consumers and producers are moderate (less than 0.185 % and 0.358 %, respectively). Our findings offer new insights into enhancing the mitigation incentives and price discovery function of China's national carbon market.

1. Introduction

The carbon market serves as a crucial policy for achieving the ambitious goals of 'carbon peaking' and 'carbon neutrality' in China. Since 2013, China has established eight pilot carbon markets, and after years of exploration, the national carbon market officially launched in July 2021, initially covering only the power sector.

As a quantitative instrument, the overall level of the emissions cap indicates the stringency and initial ambition of the carbon market. However, determining an overall cap is challenging. Uncertainties in economic development, clean energy substitution, and technological innovation have caused deviations from expectations. Meanwhile corporate pressures and economic growth may lead to overly generous allowances and low carbon prices. Unlike cap-and-trade (CAP) markets, such as the EU ETS, in which total allowances are predetermined, China's national carbon market operates as a tradable performance standard (TPS), introducing greater uncertainty, as allowances depend on benchmarks and actual outputs during the compliance period (Goulder et al., 2018, 2022; Wang et al., 2022). Rather than an overall cap, the benchmark is a crucial policy variable in the TPS market. Benchmarks typically apply to production processes with relatively uniform technological procedures that demand high-quality data on the scope of enterprise production, equipment quantities, and measurement methods. Owing to limitations in basic data, China has only established benchmarks for key sectors with high energy consumption, such as the power sector. In practice, for policy acceptability, benchmarks are set under the principle of maintaining a balance between quota surplus and deficit (Ministry of Ecology and Environment, 2024a). China's quota schemes are often announced and adjusted after production processes, which undermines the market's incentive for emission reduction and price discovery. Therefore, China's national carbon market is less efficient than those of mature carbon markets, such as the EU ETS, with lower quota turnover and quota prices, and most transactions in China are concentrated near the clearing date, displaying obvious tidal characteristics (Feng et al., 2022; Ji et al., 2024).

Over-issuance of carbon quotas and low permit prices caused by

Abbreviations: CAP, cap-and-trade; TPS, tradable performance standard; DODF, directional output distance function; I-O, input-output; MAC, marginal abatement cost.

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uncertainty are common problems many countries face in the early stages of carbon market establishment (Philibert, 2009; Pizer, 2002; Roberts and Spence, 1976; Song et al., 2022; Wang et al., 2022; Weng et al., 2018). Implementing a minimum price limit for quotas has been considered a complement instrument (Flachsland et al., 2020; Ohlendorf et al., 2022; Zhang et al., 2023). The floor-price concept has already been implemented in existing policies for GHG emissions. For example, to accelerate the phase-out of coal-fired power plants, the United Kingdom (UK) introduced a carbon floor price policy in 2013, stipulating that the transaction price of a unit carbon quota in the power sector should not be lower than £18 (Gugler et al., 2023). Germany, New Zealand, and Switzerland have also implemented a carbon price floor, which plays an important role in stabilising carbon prices and providing incentives for low-carbon investments (Ohlendorf et al., 2022; Zhang et al., 2020). China's pilot carbon markets have already allocated part of the quota with a reserved price in practice, for the purpose of carbon price discovery, market regulation, and compliance guarantees (Mo et al., 2023). In view of the problems caused by the oversupply of emission allowances, a progressive transformation from the free allocation of allowances to paid allocation is set to be introduced soon in China's national carbon (Ministry of Ecology and Environment, 2024b), this raises a fundamental issue of initial allowance price design.

2. Literature review

At an early stage, focusing on the minimum price is a feasible way to strengthen carbon constraints without excessively disrupting the carbon market. Researchers have discussed carbon floor prices based on specific objectives. For example, Abrell et al. (2019) found that to reduce the costs of the EU climate policy by up to 30 %, the optimal carbon floor price in the EU carbon market should be approximately four times higher than the average marginal abatement cost in non-ETS sectors. Newbery et al. (2019) proposed that to achieve a 40 % reduction target for 2030, a carbon floor price should be designed to 'top up' the EU carbon price to €25–30/tCO_2, and rising annually by at least 3–5 % above inflation until 2030. Brauneis et al. (2013) examined the carbon floor price that would stimulate firms to engage in irreversible emission reduction investments and proposed that the minimum carbon price in the EU ETS should be €30–35/tCO_2, respectively. Zhang et al. (2023) built a real options investment model for carbon-allowance trading markets with a price-floor mechanism and explained how different levels of carbon floor prices will affect low-carbon investments. Weng et al. (2018) discussed the level of the carbon floor price that could achieve China's climate targets with a 90 % probability; the carbon floor price was proposed to be set at \$4/tCO_2 before 2020, \$8/tCO_2 between 2021 and 2025, and \$12/tCO_2 between 2026 and 2030. These studies offer valuable insights into carbon floor prices, but they focus on particular targets and rely on assumptions about future economic trends and technological advancements. To encourage entities covered by the scheme to undertake emissions mitigation, this study defines the carbon floor price as the price level that can induce minimum abatement behaviour; that is, at least one entity would undertake abatement behaviour rather than buy quotas in the market, in which the marginal abatement cost (MAC) is a crucial factor influencing the entity's choice. China's current national carbon market is based on differing regional emission costs in the power sector (Zhang et al., 2018). More recently, an official draft plan declared to expand the national carbon market to include the cement, steel, and aluminum industries that the cement, steel, and electrolytic aluminium sectors were prepared to join the market in 2024 (Ministry of Ecology and Environment, 2024c). Considering that more high-carbon industries from different regions will be included in the national market in the near future, this study sets the carbon floor price according to the lowest regional MAC. The logic behind is that the emission intensities of the regulated power entities are usually higher than those of their regional economy as a whole. Therefore, the floor price set by the lowest regional MAC would be at least higher than the MACs of regulated entities coming from that region, thus encouraging those entities to take mitigation actions rather than buy quotas with a floor price or even a higher transaction price on the market.

Various methods can be used to estimate MACs, including macroeconomic models, such as the computable general equilibrium model (Tang et al., 2020; Yao and Liang, 2016), input-output (I-O) models with multi-objective planning (Hristu-Varsakelis et al., 2010; Minihan and Wu, 2012), and the distance function method (Liu et al., 2016; Peng et al., 2018; Wang et al., 2017). Owing to the inherent uncertainty involved in the first two methods, which require assumptions regarding elasticity coefficients, economic growth, and technological progress, the accuracy of their results is often contentious. Consequently, scholars have opted for the distance function method, which imposes fewer data requirements and relies on fewer assumptions, thereby enhancing the robustness of the analysis (Fare et al., 1993; Hailu and Ma, 2017; He, 2015; Wu et al., 2019; Xiao et al., 2017). Among the various distance function methods, the directional output distance function (DODF) is widely used in regional or industrial MAC analyses because of its ability to accommodate non-radial changes between desirable and undesirable outputs, reflecting actual production conditions (Färe et al., 2005). However, traditional DODF methods may overestimate the MACs for inefficient production units because they assume that these units can achieve maximum efficiency by adjusting the production modes (Ma et al., 2019). Moreover, different directional vectors significantly impact estimation. To address these limitations, Kuosmanen and Zhou (2021) introduced quantiles into a non-parametric directional distance function method to mitigate inefficiency, directional vector selection, and data noise issues. However, the non-parametric distance function might not be derivable and is susceptible to data outliers; therefore, it fails to estimate MACs. This study addresses this issue by combining the quantile and parametric DODF to estimate the MAC for a production unit.

Avoiding the high economic costs of pricing approaches is a key consideration for policy-makers. In this vein, Mardones and Alvial (2024) utilised an I-O price model to assess price variations associated with diverse carbon tax rates. Llop (2020) employed an enhanced I-O price model to analyse the ramifications of energy price shifts on domestic prices. Given that the carbon floor price mainly influences domestic product prices, instead of the competitive I-O price model used in the previous literature, a non-competitive I-O price model is built in this study to simulate the cost-push effect of quotas bought at the floor price in China.

With the aim of promoting the efficiency and mitigation function of China's national carbon market with minimal intervention, we suggest setting the carbon floor price complementary to the current benchmark approach. However, the literature on this topic is rather sparse. Focusing on floor price setting, we estimate the regional equivalent MACs by a quantile parametric directional output distance function method and set the carbon floor prices for years 2021–2024 accordingly. Moreover, we simulate the short-term effects of a floor price using a non-competitive input-output price model, which are of particular importance for assessing the policy outcomes. The logical structure of the study is shown in Fig. 1. By offering a distinctive interpretation of the carbon floor price and an improved method of MAC estimation from previous literature in the area, this study provides a much-needed reference for setting an initial price for the quota in China's national carbon market.

The remainder of this paper is organised as follows. Section 3 illustrates the methodology. Section 4 presents an estimation of carbon floor prices and verifies their feasibility and necessity. Section 5 presents a simulation of the short-term effects of a carbon floor price. Section 6 concludes.

3. Methodology

The approach developed in this paper comprises two stages: the first step consists of constructing a quantile parametric DODF that is used to

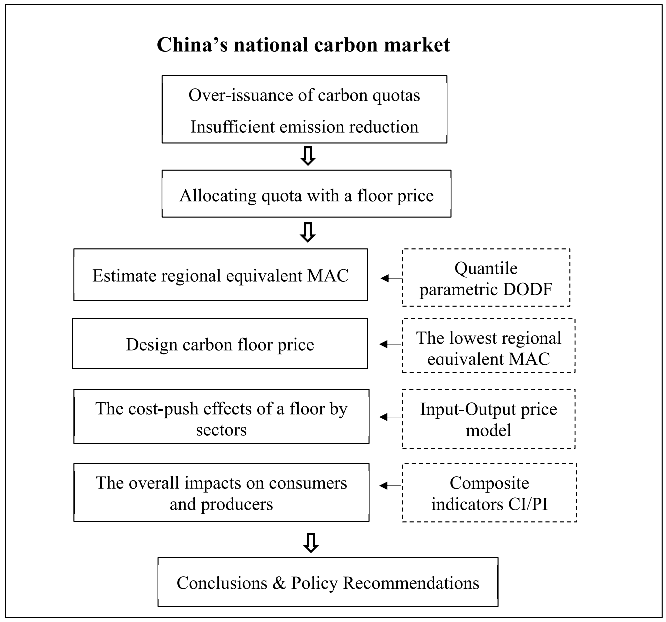

Fig. 1. The logical framework diagram.

estimate the MACs, proving a theoretical reference for setting carbon floor price. In the second step, a non-competitive I-O price model is employed to depict how the carbon floor price would change the prices that producers and consumers face, consequently, the potential cost-push impacts of various implementations of a floor price are examined.

3.1. Quantile parametric DODF

The choice of production set in the parametric DODF used to estimate the MAC yields varying results. Many studies have employed a production set in which three inputs (labour, capital, and energy) are utilised to produce a desirable output (gross domestic product [GDP]) and an undesirable output (CO_2 emissions). CO_2 emissions are typically estimated based on energy consumption, and there is a strong correlation between them (Ma et al., 2019). Thus, including the energy consumption as an input weakens the accuracy of the estimated MAC. This can be proved by assuming that the distance function can be expressed as

$$d = \varphi(z_1, z_2, y_1, b_1) \tag{1}$$

z_1 *and* z_2 represent two inputs; y_1 *and* b_1 represent the desirable and undesirable outputs, respectively. When there is a correlation between z_1 and b_1, the distance function d with respect to the undesired output b_1 is derived by Eq. (2). However, the current MAC calculation formula does not include the second term on the right-hand side of Eq. (2), leading to biased results.

$$\partial d / \partial b_1 = \partial \varphi / \partial b_1 + \partial \varphi / \partial z_1 (\partial z_1 / \partial b_1) \tag{2}$$

The aforementioned correlation also poses challenges for estimating parameters for the DODF using linear programming or regression methods, which may diminish the rank of the coefficient matrix of unknown parameters in linear programming, potentially leading to an infeasible solution. This may lead to the coefficients obtained through the regression method failing the significance test. Consequently, we consider only two inputs, capital and labour, in the estimation of MACs. Additionally, the null-jointness assumption for the output set was adopted to improve the fitness of the DODF, which means that the DODF value is negative when the undesirable output is zero.

Because the regression method requires a substantial volume of data and lacks the capability to enforce monotonicity on the distance function (Hailu and Ma, 2017), we adopt the linear programming method to solve the distance function. Following Kuosmanen and Zhou (2021), this study incorporates quantiles into the parametric DODF to address the issues of directional vector selection and short-term production adjustment for inefficient production units, as follows:

$$\text{Min} \ \ (1-\tau)\sum_{i=1}^{n}\varepsilon_i^- + \tau\sum_{i=1}^{n}\varepsilon_i^+ \tag{3}$$

s.t.

$$\vec{D}(\boldsymbol{x}_i, y_i, b_i; 1, -1) = \alpha_0 + \beta_1 y_i + \gamma_1 b_i + \sum_{k=1}^{K}\alpha_k x_{ik} + \frac{1}{2}\sum_{k=1}^{K} \times \sum_{k'=1}^{K}\alpha_{kk'}x_{ik}x_{ik'} + (1/2)\beta_2 {y_i}^2 + (1/2)\gamma_2 {b_i}^2 + \sum_{k=1}^{K}\delta_k x_{ik} y_i + \sum_{k=1}^{K}\eta_k x_{ik} b_i + \mu y_i b_i, k = 1, \ldots, K, i = 1, \ldots, n$$

$$\vec{D}(\boldsymbol{x}_i, y_i, b_i; 1, -1) + \varepsilon_i^+ - \varepsilon_i^- = 0, i = 1, \ldots, n$$

$$\vec{D}(\boldsymbol{x}_i, y_{ik}, 0; 1, -1) < 0, i = 1, \ldots, n$$

$$\partial \overrightarrow{D}(\boldsymbol{x}_i, y_i, b_i; 1, -1) \Big/ \partial b_i \geq 0, i = 1, \ldots, n$$

$$\partial \overrightarrow{D}(\boldsymbol{x}_i, y_i, b_i; 1, -1) \Big/ \partial y_i \leq 0, i = 1, \ldots, n$$

$$\partial \overrightarrow{D}(\boldsymbol{x}_i, y_i, b_i; 1, -1) \Big/ \partial x_{ik} \geq 0, i = 1, \ldots, n$$

$$\beta_1 - \gamma_1 = -1, \beta_2 = \mu = \gamma_2, \delta_k = \eta_k, k = 1, 2$$

$$\alpha_{kk'} = \alpha_{k'k}, k = 1, 2$$

$$\varepsilon_i^+, \varepsilon_i^- \geq 0, i = 1, \ldots, n$$

ε_i^- and ε_i^+ represent the negative and positive deviations from the production frontier of production unit i , respectively. k represents the input type, $\boldsymbol{x_i}$ is the input vector of production unit i, y_i and b_i are the desirable and undesirable outputs of production unit i, respectively. τ represents the weight of positive deviation, and $(1-\tau)$ is the weight for negative deviation. When $\tau = 0$, Eq. (3) represents the traditional parametric DODF. The first set of equality constraints in Eq. (3) represents the quadratic DODF formula. The second set of equality constraints can be interpreted as multivariate regression equations. The third set of constraints imposes the non-jointness assumption. The fourth, fifth, and sixth sets of inequality constraints ensure that the directional distance function is monotonic, guaranteeing a positive shadow price. The seventh and eighth sets of equality constraints impose the translation property and symmetry, respectively.

When using quantile parametric DODF to estimate MACs, the number of quantiles can be considered as a tuning parameter specified by the user, depending on the sample size. In principle, the number of quantiles can be set equal to the sample size n, but for most applications, a smaller number of quantiles seems sufficient. Like other studies (Dai et al., 2020; Kuosmanen and Zhou, 2021; Wen et al., 2022), this study also set $\tau = (0.05, 0.15, 0.25, \ldots, 0.85, 0.95)$.

3.2. Estimation for MAC

Using the DODF value of each production unit by quartile, the MAC of each unit at different quartiles can be acquired based on the parity between the DODF and the revenue function. Referring to Fare et al. (1993), the revenue function is set as follows:

$$R(\boldsymbol{x}, p, q) = \max \left\{ py - qb : \overrightarrow{D}(\boldsymbol{x}, y, b; 1, -1) \geq 0 \right\} \tag{4}$$

p and q are the prices of desirable and undesirable outputs, respectively. R represents the maximum revenue that a production unit can obtain at desirable output price p and undesirable output price q. Given that the distance function represents the maximum distance that a production unit can move along direction vector $\boldsymbol{g}\,(1, -1)$ towards the production frontier, Eq. (4) can be expressed as

$$R(\boldsymbol{x}, p, q) = max_{y,b} \left\{ (py - qb) + p\overrightarrow{D}(\boldsymbol{x}, y, b; \boldsymbol{g}) - q\overrightarrow{D}(\boldsymbol{x}, y, b; \boldsymbol{g}) \right\} \tag{5}$$

As the parametric DODF is differentiable, the first-order conditions for the desirable and undesirable outputs can be obtained as follows:

$$\nabla_y \overrightarrow{D}(\boldsymbol{x}, y, b; 1, -1) = -\mathrm{p} \Big/ (\mathrm{p} - \mathrm{q}) \tag{6}$$

$$\nabla_b \overrightarrow{D}(\boldsymbol{x}, y, b; 1, -1) = \mathrm{q} \Big/ (\mathrm{p} - \mathrm{q}) \tag{7}$$

Assuming that the price of the desirable output is equal to one, the shadow price of the undesirable output can be obtained using Eq. (8):

$$q = -\left(\partial \overrightarrow{D}(\boldsymbol{x}, y, b; 1, -1) \Big/ \partial b \right) \Big/ \left(\partial \overrightarrow{D}(\boldsymbol{x}, y, b; 1, -1) \Big/ \partial y \right) \tag{8}$$

3.3. Theoretical reference for the carbon floor price

In a paid allocation situation, by comparing the market price per carbon quota with their MACs, entities covered by the market would choose between taking an abatement action and buying a quota. However, in practice, most carbon markets allocate quotas free of charge; thus, the carbon costs faced by the covered entities are simply payments for their quota shortfalls. To design a floor price to stimulate abatement actions under such circumstances, the revenue function in Eq. (5) must be adjusted accordingly to determine the equivalent MAC of the floor price of carbon.

In China's national carbon market, a clearing cap has been adopted to control the pressure on market participants (Ministry of Ecology and Environment, 2024a); that is, participants pay at most 20 % of their total carbon emissions. To some extent, this cap represents an acceptable level of carbon cost under current situation in China. Therefore, we consider this as the starting point for introducing a quota price. Following this idea, a discount rate of 20 % was incorporated into the revenue function to estimate the equivalent MAC for the floor price of the quota. Eq. (5) is rewritten as

$$R(\boldsymbol{x}, p, q) = max_{y,b} \left\{ (py - 0.2qb) + p\overrightarrow{D}(\boldsymbol{x}, y, b; \boldsymbol{g}) - q\overrightarrow{D}(\boldsymbol{x}, y, b; \boldsymbol{g}) \right\} \tag{9}$$

The adjusted shadow price of the undesirable output can be calculated using the following equation:

$$q = -0.2 \left(\partial \overrightarrow{D}(\boldsymbol{x}, y, b; \boldsymbol{g}) \Big/ \partial b \right) \Big/ \left(\partial \overrightarrow{D}(\boldsymbol{x}, y, b; \boldsymbol{g}) \Big/ \partial y \right) \tag{10}$$

Then, we follow Kuosmanen and Zhou (2021) by taking the average of the equivalent MACs under the two closest quantiles for the production unit, except for the following three cases. (1) If the production unit lies exactly on quantile τ^*, we use the average of the equivalent MACs under quantiles $\tau^* + 0.1$ and $\tau^* - 0.1$. (2) If τ^* is 0.95, use the equivalent MAC for the 95th quantile. (3) If the production unit lies below the 0.05th quantile, an equivalent MAC for the 0.05th quantile. This setting allows us to gain the equivalent MAC not only on the frontier but also in the interior of the production possibility set. Meanwhile, the estimates are robust to data noise and the choice of direction vector.

Based on the provincial equivalent MACs, we suggest setting a uniform floor price based on the lowest regional equivalent MAC in China's national market. Specifically, the carbon floor price is determined as follows:

$$P_{floor,t+1} = min\left(MAC_{i,t}\right) \quad i = 1, 2 \ldots 30 \tag{11}$$

where $P_{floor,t+1}$ represents the carbon floor price for year $t+1$, $MAC_{i,t}$ is the equivalent MAC for the floor price of region i in year t. Based on Eq. (11), the carbon floor price can be set at the beginning of each year and used to allocate quotas by the government in the primary market.

3.4. Non-competitive I-O price model

The price levels chosen by the regulator act as focal points influencing the market price of allowances and the decision-making of prospective participants. Given the potential cost effect of pricing carbon, a non-competitive I-O price model is adopted to estimate the short-term price effects of introducing a minimum price for emission quotas.

The I-O price model illustrates that the unit price of output in each sector can be represented as the total expenditures on intermediate inputs and primary inputs (e.g. employee compensation, indirect taxes, and operating surplus) as follows (Leontief, 1986):

$$\boldsymbol{p} = \boldsymbol{A}'\boldsymbol{p} + \boldsymbol{v} \tag{12}$$

$\boldsymbol{p}$ is a $n \times 1$ column vector of sectoral prices, $\boldsymbol{A}'$ is the transpose of the $n \times n$ intermediate input coefficients matrix $\boldsymbol{A}$, and $\boldsymbol{v}$ is a $n \times 1$ column vector of primary inputs per unit. This study employs a non-competitive

I-O price model to analyse how changes in a sector's primary inputs resulting from the implementation of a carbon floor price propagate through the production chain and affect prices in other sectors. This model simulates the network structure of the Chinese economy, distinguishing between domestic and imported products to avoid overestimating sectoral price changes. Eq. (12) can be rewritten as follows:

$$\boldsymbol{p} = \boldsymbol{A}_{D}^{\prime}\boldsymbol{p} + \boldsymbol{A}_{M}^{\prime}\boldsymbol{p}^{\boldsymbol{M}} + \boldsymbol{v} \tag{13}$$

where $\boldsymbol{A}_{D}^{\prime} + \boldsymbol{A}_{M}^{\prime} = \boldsymbol{A}^{\prime}$, $\boldsymbol{p}^{\boldsymbol{M}}$ is an $n \times 1$ column vector of the import price. Assuming constant quantities within a price model, we adopt this approach to assess the cost-push impact of various implementations of a carbon floor price. As compensation of the environment damage, the costs induced by paid quotas, namely, Δv_k, are translated into an increment in the value added of products in covered sectors and defined as

$$\Delta v_k = \delta_k I_k p_f \tag{14}$$

where δ_k is the ratio of paid quota for the covered sector k, I_k is its carbon intensity, p_f is the carbon floor price. As the imported price is not affected by domestic price, the subsequent price changes ($\Delta \boldsymbol{p}$) can be determined by the following equation:

$$\Delta \boldsymbol{p} = \left(\boldsymbol{I} - \boldsymbol{A}_{D}^{\prime}\right)^{-1} \begin{bmatrix} \Delta v_1 \\ \Delta v_2 \\ \dots \\ \Delta v_n \end{bmatrix} \tag{15}$$

In addition to the price change by sector, the overall impacts of the carbon floor price on consumers and producers are considered. Referring to the representative basket of goods and services of the consumer price index and producer price index, two composite indicators, *CI* and *PI* are constructed through weighting the price changes caused by the carbon floor price in products and services with their corresponding consumer consumption and outputs, respectively. The detailed formulas are

$$CI = \sum_{i=1}^{n} \Delta p_i f_i \tag{16}$$

$$PI = \sum_{i=1}^{n} \Delta p_i z_i \tag{17}$$

where *CI* measures the overall impact of the carbon floor price on consumers and *PI* measures the overall impact of the carbon floor price on producers. Δp_i represents the price change caused by carbon floor price in sector i. f_i is the proportion of consumption from sector i in the total consumer consumptions, z_i is the proportion of output from sector i in the total outputs.

Table 1
Provincial distribution of enterprises covered by the national carbon market.

Province	Number	Province	Number
Hebei	94	Shanxi	117
Xinjiang	100	Beijing	14
Qinghai	12	Jilin	44
Sichuan	55	Jiangxi	50
Hainan	10	Liaoning	90
Anhui	79	Guizhou	37
Hubei	58	Chongqing	29
Shandong	304	Jiangsu	210
Fujian	44	Shaanxi	64
Heilongjiang	105	Henan	117
Guangdong	127	Tianjin	25
Zhejiang	159	Shanghai	30
Gansu	24	Inner Mongolia	193
Ningxia	44	Yunnan	22

Data sources: https://www.cets.org.cn/.

4. Estimation of carbon floor price

Table 1 shows the distribution of enterprises covered by China's national carbon market in 2023. Except for Tibet, all other provinces have a certain number of enterprises. This explains why we choose regions other than Tibet as the production units to estimate the carbon floor price.

4.1. Variables and data

Specifically, we estimate the regional equivalent MACs (except Tibet) based on the following variables. Labour (x_1) is denoted by the number of employees at the end of a year for each province. As there is no official announcement of capital stock data in China, we estimate capital (x_2) using the classic perpetual inventory method, as follows:

$$K_t = I_t + K_{t-1}(1-\delta) \tag{18}$$

where K_t and K_{t-1} are the capital stock in year t and $t-1$, respectively, I_t is the total investment in fixed assets in year t which is deflated to 2013 constant price by the fixed asset price index of year t, the empirical value for the depreciation rate δ is 6 % (Shan, 2008; Zhang et al., 2004).

The desirable output (y) is denoted by the GDP of each province which is deflated to 2013 constant price by the GDP price index. Given that carbon emissions from fossil energy combustion account for a large proportion of total carbon emissions in China, the undesirable output carbon emission (e) is considered only in this section and is estimated by following the 2006 IPCC Guidelines (2006 IPCC Guidelines for National Greenhouse Gas Inventories):

$$e = \sum_{i=1}^{m} E_i NCV_i CF_i COF_i 44 \Big/ 12 \tag{19}$$

where m is the energy variety number, E_i represents the consumption of energy i, NCV_i, CF_i, COF_i represent the average low-level heat production, carbon content per unit calorific value, and carbon oxidation rate of energy i.

In the estimation of MACs using quantile parametric DODF, the more production data are available, the more accurate are the results. China began its pilot carbon trading markets in 2013; however, the fixed asset investment price index was no longer available from China's National Bureau of Statistics after 2018; therefore, we estimate the regional equivalent MACs of 30 Chinese provinces (excluding Tibet) for the year 2013–2018. Data are sourced from the *Provincial Statistical Yearbooks* (2014–2019) and *Energy Statistical Yearbooks* (2014–2019).

4.2. Regional equivalent MACs for the carbon floor price

Table 2 describes the input and output variables for the 30 Chinese provinces for the years 2013–2018. There are large differences in the levels of economic development, resource endowment, and carbon emissions across the provinces. Consequently, the equivalent MACs are significantly different in each province.

To avoid the non-convergence problems caused by difference in data size, the input and output variables are standardized by dividing each variable with its mean value before solving the DODF by linear programming method. Then, the parametric DODF under different quantiles are estimated by the software GAMS, parameter estimations for Eq.

Table 2
Descriptive statistics of the input and output variables.

Variable	Unit	Mean	Std. Dev.	Max	Min
Labour (x_1)	10^4 persons	982.24	827.48	4585.20	66.50
Capital (x_2)	10^9 CN¥	99,997.86	66,055.96	322,642.40	9411.42
GDP (y)	10^9 CN¥	20,865.35	15,542.22	69,495.45	1953.57
CO_2 (e)	10^4 t	45,637.29	31,577.63	156,469.65	5846.52

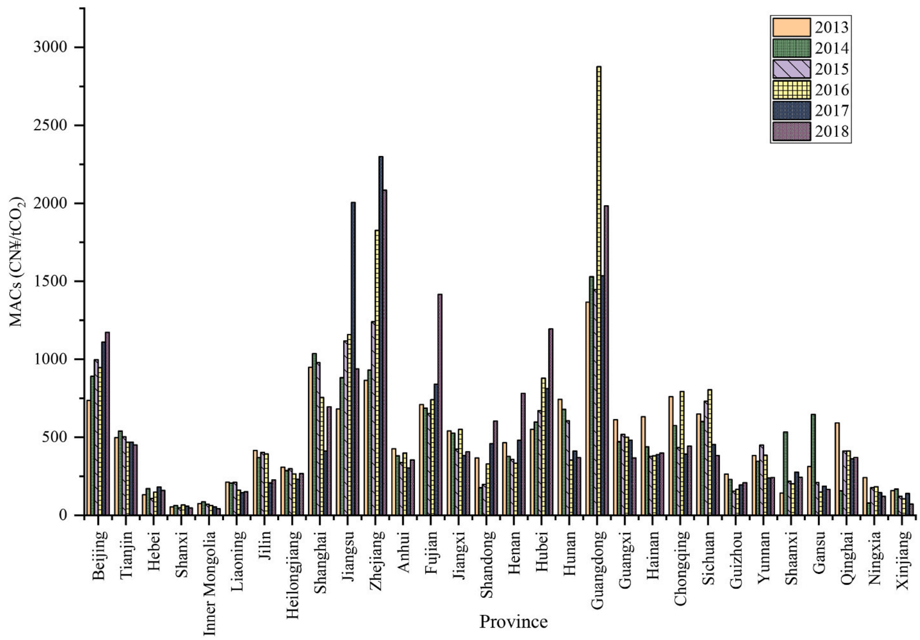

Fig. 2. Equivalent MACs of each province for the year 2013–2018 (in 2013 price).

Table 3
Estimation of carbon floor prices for years 2020–2024 Unit: CN¥/tCO_2.

Year	2020	2021	2022	2023	2024
Carbon floor price	58.31	59.68	61.17	62.95	64.21

(3) under 10 quantiles are presented in Appendix Table A1, and the largest quartiles in each year which corresponds to the positive deviations from the frontier in each province are selected (see Appendix, Table A2). The corresponding quartiles vary from province to province during different years within 2013–2018 because of differences in production structure and technology. This indicates that traditional parametric DODF used for estimating MACs fails to capture the adjustments made by inefficient production units and may lead to estimation errors.

By combining the quantiles in Table A2 with the adjusted shadow prices in Eq. (10), the regional equivalent MACs corresponding to the carbon floor prices are estimated, as Fig. 2 shows.

In Fig. 2, there are significant variations in the equivalent MACs across the provinces. On average, Guangdong has the highest equivalent MAC of CN¥1789.38/tCO_2, while Shanxi has the lowest equivalent MAC of CN¥56.09/tCO_2, this is consistent with the conclusion that regional MACs are inversely changes with their carbon emission intensities (Cheng et al., 2022). The differences in regionally equivalent MACs make it difficult to set uniform carbon prices. Moreover, from a temporal perspective, some regions, such as Gansu, Ningxia, and Xinjiang, show a general decline in their equivalent MACs, whereas others such as Beijing, Guangdong, and Zhejiang, demonstrate an upward trend in their equivalent MACs. These divergent trends further highlight the widening disparities in equivalent MACs among Chinese regions. In such a situation, it is more feasible to introduce a minimum price for the quotas with the aim of motivating overall abatement efforts, especially those with low MACs and high abatement potential, to take mitigation actions rather than buy the quotas on the market.

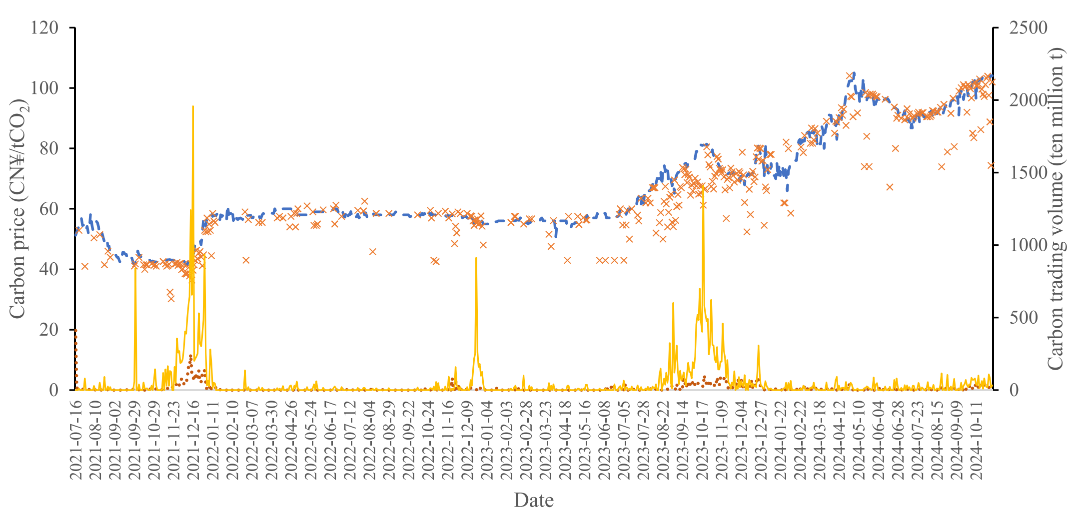

Fig. 3. Trading prices and volumes in China's national carbon market.
Data sources: https://data.csmar.com/.

Table 4
Carbon market trading data and carbon floor prices for the year 2021–2024 Unit: CN¥/tCO_2.

Year	2021	2022	2023	2024
Average listing price	47.16	57.54	73.42	94.93
Average bulk price	41.95	54.98	67.11	89.99
Maximum listing price	58.7	61.38	81.42	105
Minimum listing price	41.46	55	50.52	66
Maximum bulk price	52.92	62.54	80.51	104.1
Minimum bulk price	30.21	42.54	42.96	54.58
Carbon floor price	59.68	61.17	62.95	64.21
Percentage of listing volume(%)	17.21 %	12.22 %	16.51 %	30.17 %
Percentage of bulk volume(%)	82.79 %	87.78 %	83.49 %	69.83 %

Data sources: https://data.csmar.com/.

4.3. Carbon floor price setting

As the regional equivalent MACs could no longer be estimated directly after 2018, we referred to the method of the Regional Greenhouse Gas Initiative (RGGI) to set the carbon floor price for subsequent years (RGGI, 2024); that is, the floor price is adjusted annually according to the consumer price index (*CPI*), as follows:

$$P_{floor,t+1} = P_{floor,t} CPI_t \ \mathrm{t} = 2019 \tag{20}$$

where $P_{floor,t}$ is the latest available value of the carbon floor price determined by Eq. (11), in 2019. Multiplied by CPI_t for the same year, the initial value $P_{floor,t}$ (the lowest regional equivalent MAC of year $t-1$) was adjusted to represent the regional equivalent MAC of year t, to determine the value of the carbon floor price for the subsequent year $t+1$.

Based on Eq. (20), the suggested carbon floor prices for China's national carbon market for the years 2020–2024 are shown in Table 3, which shows that the floor prices are increasing annually.

4.4. The need to introduce a carbon floor price

To verify the necessity of introducing the carbon floor price into China's national carbon market, we compared our suggested carbon floor prices with the market carbon prices from July 2021 to October 2024. As Fig. 3 shows, the market prices fluctuated from CN¥30/tCO_2 to CN¥105/tCO_2, and the trading volume was mainly concentrated around each compliance period (31 December).

For comparison, the daily market price is converted into the annual average price using Eq. (21).

$$P_m = \sum\nolimits_t (P_t TR_t) \Big/ \sum\nolimits_t TR_t \tag{21}$$

where P_m is the average market price and P_t and TR_t represent the price and trading volume on day t, respectively. The results for the years 2021–2024 (where 2024 covers trading data from 1 January to 31 October) are summarised in Table 4.

As Table 4 shows, the national carbon market is dominated by block transactions, accounting for 69.8 %–87.8 % of the total trading volume during the observational period. This indicates that the covered entities tend to fulfil their obligations through block trades. Moreover, the price for block transaction is basically lower than the listing price, and with even bigger vitality range from CN¥30.21/tCO_2 to CN¥88.4/tCO_2 in 2021, CN¥42.54/tCO_2 to CN¥62.54/tCO_2 in 2022, CN¥42.96/tCO_2 to CN¥88.4/tCO_2 in 2023 and CN¥54.58/tCO_2 to CN¥104.1/tCO_2 in 2024. During the first compliance cycle of 2021–2022, the average carbon prices of both listed and bulk agreement trading in China's national carbon market were consistently lower than our suggested floor prices (CN¥59.68/tCO_2 for 2021, and CN¥61.17/tCO_2 for 2022). In this context, covered entities facing quota shortages tend to opt to purchase allowances in the market instead of adjusting their production for compliance, which challenges the market objectives of incentivising abatement and fostering low-carbon investment. While during the second compliance cycle of 2023–2024, the average market carbon prices of the listed and bulk agreement trading both exceed our suggested floor prices due to the recent regulation reform and strengthen, such as introducing tighter limits, severe penalties for violations and reduction of free allocations (Ministry of Ecology and Environment, 2024a), which imposes market prices to rise steadily with the average price rising to CN ¥94.5/tCO_2 by the end of October 2024. However, it should be noted that as the major way the market participants fulfil their obligations, the lowest price for block transaction is only CN¥42.96/tCO_2 and CN ¥54.58/tCO_2 in 2023 and 2024, respectively; which are rather lower than our suggested floor prices (CN¥62.95/tCO_2 for 2023, and CN ¥64.21/tCO_2 for 2024). Combined with sharp fluctuations in prices, bulk agreement trading increases the risk to low-carbon investors, and it is difficult to set reliable incentives for abatement efforts. As a tool that aligns with the market objective of reducing carbon emissions with minimum social abatement costs, the carbon floor price deserves more attention in the process of national carbon market optimisation in China, especially as a complementary instrument to ensure that participants with lower MACs take initiative abatement actions rather than resort to block allowance purchases.

4.5. The feasibility of introducing a carbon floor price

China's 14th Five-Year Plan for renewable energy development has proposed the targets of annual electricity generation from renewable energy reaches 3.3 trillion kWh, and the consumption proportion of electricity from renewable energy reaches 33 % by 2025. To fulfil these targets and reduce the huge financial pressure caused by renewable energy subsidies, China launched green power trading in 2021 based on green certificates, which are designed to enable the producers of renewable energy power to obtain subsidies through market mechanisms. The price of green electricity consists of two parts: the coal-based electricity benchmark price and the environmental premium, which is an additional cost that consumers are willing to pay for better environmental performance. From the perspective of substitute goods, this environmental premium indicates the external cost of carbon emissions, which can be easily translated into the price of carbon emissions per ton (P_g) using Eq. (22).

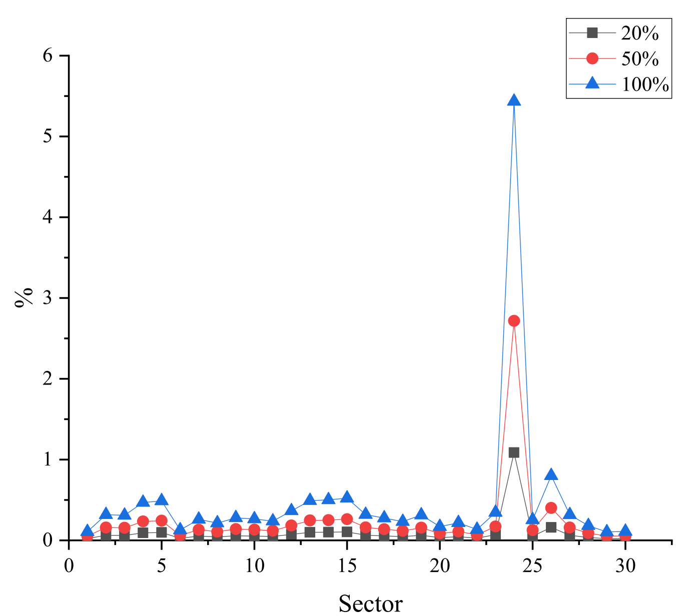

Fig. 4. Price increments of all sectors under 20 %, 50 %, 100 % paid scenarios.

$$P_g = gpre / (C_{coal} I_{coal}), \quad (22)$$

where *gpre* is the environmental premium for green electricity, C_{coal} is the coal consumed per unit of coal power production, I_{coal} is the carbon emissions coefficient per unit of coal.

The World Resources Institute's report showed that, the average unit price of green power (*gpre*) in 2022 was about CN¥0.08/kWh higher than the coal-based electricity benchmark price for the State Grid of China, and about CN¥0.05–0.06/kWh higher for the Southern Power Grid of China. According to data published by the Chinese National Energy Administration, the coal consumption rate (C_{coal}) in 2022 is 304.8 g/kWh, and the carbon emission coefficient per unit of coal (I_{coal}) is 2.493. Based on this data, the cost of carbon emissions embodied in the green electricity price for 2022 can be estimated using Eq. (22); the results are presented in Appendix Table A3.

Because the green electricity trading market lacks uniform management, environmental premiums vary across different power grids. In 2022, the cost of carbon emissions embodied in the green electricity price ranges from CN¥65.8/tCO_2 to CN¥105.3/tCO_2. Our suggested carbon floor price for 2022 is CN¥61.17/tCO_2, it is very close to the lower bound of environmental premium interval for green electricity. Therefore, in terms of substitute goods, introducing a carbon floor price as a cost to the power sector covered by China's national carbon market is reasonable and acceptable. As the lower limit of the carbon market price, a floor price would also help promote electricity generation from renewable energy sources in China.

5. Simulation of paid quota allocation with a carbon floor price

The carbon floor prices set in this study provide an important reference for a paid quota scheme, and the proportion of paid quotas is another relevant element for quantifying their impact in practice. We set three scenarios based on the practical situation in China and the experience of a mature market. Nowadays, entities covered by China's national carbon market are capped at 20 % of their actual emissions; therefore, we take 20 % as the initial share of the quota allocated with floor price to power entities. Drawing on the EU carbon market's 100 % paid quota for the power sector, we set the maximum share of the paid quota at 100 %. Considering the necessity of a gradual transition from free to paid allocation, we set a 50 % paid scenario. Using the 2020 non-competitive I-O table, the short-term price effect by sector under each scenario is simulated using Eq. (15).

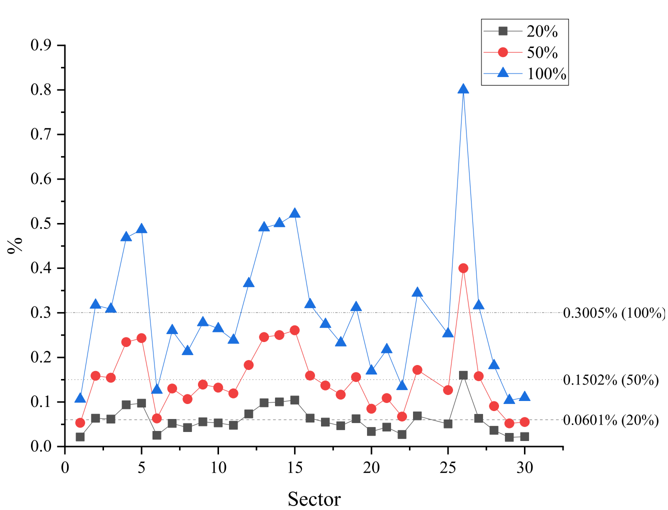

Fig. 5. Price increments of the non-covered sectors under 20 %, 50 %, 100 % paid scenarios.

5.1. Structure of the cost effects induced by a carbon floor price

As Fig. 4 shows, introducing a carbon floor price raises the production cost and price in the market-covered power sector (sector 24). Under scenarios of 20 %, 50 %, and 100 % quota allocated with a floor price of CN¥58.31/tCO_2 for the year 2020, the price increments for sector 24 are 1.0867 %, 2.7166 %, and 5.4333 %, respectively. Because of the production linkages among sectors, the production sectors other than sector 24 are also affected indirectly through their intermediate inputs, but with relatively lower price increments, ranging from 0.0207 % to 0.16 % under the 20 % scenario, 0.0519 %–0.4 % under the 50 % scenario, and 0.1037 %–0.8 % under the 100 % scenario.

To clarify this, we show the price increments of the non-covered sectors in Fig. 5. Among these sectors, the top seven price increments appear in sectors 4 (metal mineral extraction products), 5 (non-metallic and other mineral extraction products), 12 (chemistry), 13 (non-metallic mineral products), 14 (metal smelting and rolling products), 15 (metal products), and 26 (water production and supply), which are significantly higher than the average price change for the entire economy (i.e. 0.0601 %, 0.1502 %, and 0.3005 %) under each scenario. Most of these sectors are expected to be included in China's national carbon market; thus, introducing a carbon floor price equivalent to an indirect expansion of the carbon market.

5.2. Aggregate cost effects induced by a carbon floor price

The cost-push effect of the carbon floor price in the production sector inevitably affects the consumption and production of society as a whole. Controlling for its potential negative impacts is a prerequisite for implementing the carbon floor price. Based on Eqs. (16) and (17), the composite indices *CI* and *PI* are calculated, and both of them are positively proportional to the share of paid quotas; specifically, the *CI* increases by 0.037 %, 0.0925 %, and 0.1850 % under the 20 %, 50 %, and 100 % paid share scenarios, respectively, while the *PI* increases by 0.0717 %, 0.1793 %, and 0.3585 %, respectively, in each corresponding scenario. This indicates that introducing a carbon floor price in the national carbon market has a more pronounced impact on the *PI* than that on the *CI*, but the changes in both indices, even under the 100 % paid scenario, remain below 0.2 % and 0.4 %, respectively. The results indicate that the overall impacts of carbon floor prices on consumer welfare and economic operations are relatively mild. In other words, the risk that emissions allowance floor prices may translate into significantly higher inflation in the near term appears limited.

6. Conclusions

As a market-based policy instrument, China's national carbon market plays a crucial role in promoting its transition to a low-carbon economy. However, the current market is characterised by quota overallocation and market prices disconnected from abatement costs, and it is imperative to introduce price mechanisms to address issues such as inefficient market function and inadequate emission constraints. Therefore, this study proposes the concept of a carbon floor price from the perspective of ensuring emission reduction incentives and conducts a systematic study on the quota floor price for China's national carbon market. Our findings offer valuable insights into the improvement of China's national carbon market, and the main conclusions and policy implications are as follows:

First, for the years 2021–2024, the covered entities mainly fulfilled their obligations through block trades, with lower and higher vitality prices than the market listing price, and the lowest block transaction prices fell below our suggested carbon floor prices in each year, which is CN¥59.68/tCO_2, CN¥61.17/tCO_2, CN¥62.95/tCO_2, and CN¥64.21/tCO_2, respectively. This situation helps us understand why entities covered by the national market would choose to buy quotas rather than take abatement actions; this obviously violates the market objective of reducing carbon emissions with minimum social abatement costs. Therefore, a carbon floor price is urgently needed in China to internalise the cost of carbon emissions and to provide assurance that the market carbon price will exceed that level.

Second, compared to the price of green electricity, our suggested carbon floor price is very close to the lower limit of the embodied carbon cost interval for green electricity. This indicates that in terms of substitute goods, our suggested carbon floor price is reasonable. Given the potential cost-push effect on thermal power sectors covered by China's national carbon market, a carbon floor price for the emission quota would be helpful in encouraging a switch to green electricity in China.

Third, regardless of the share of paid quota, besides the market-covered power sector (sector 24), the cost-push effect of carbon floor price on the non-covered sectors 4 (metal mineral extraction products), 5 (non-metallic and other mineral extraction products), 12 (chemistry), 13 (non-metallic mineral products), 14 (metal smelting and rolling products), 15 (metal products), and 26 (water production and supply) are all significantly higher than the average effect in the entire production system. This indicates that a carbon floor price has the additional function of indirectly expanding the national carbon market, which is another crucial issue facing by policy-makers.

Fourth, considering the economy as a whole, the cost-push effect of the carbon floor price on consumers and producers is moderate. Even if the authority offers to sell all quotas at the floor price, the potential changes in the composite consumers' impact index *CI* and producers' impact index *PI* are only 0.185 % and 0.3585 %, respectively. This means that in terms of cost containment, introducing a minimum price limit for quotas is feasible for China's national carbon market.

In line with the "dual carbon" goals, China has made unwavering efforts to improve relevant policy for the national carbon market. Among which, the transition from free to paid quota allocation has been proposed to overcome oversupply of allowances. To avoid the high economic costs of pricing carbon, the Chinese government should set a relatively low initial quota price as guidance and gradually adjust it through market mechanisms to reach a reasonable level, that is, be high enough to stimulate the covered power entities to take abatement actions into account. To fulfil this target, the carbon floor prices set in this study provide an important reference for a paid quota scheme. Moreover, given that the overall impacts of the floor price on consumers and producers are moderate, the carbon floor prices could also to be used as the minimum limit for the transaction price of a unit carbon quota in the secondary market, thereby making carbon prices more accurately reflect the covered entities' MACs and giving them a stronger impetus for emission reduction.

It should be pointed out that, in the absence firm-level data, we suggest setting a uniform floor price based on the lowest regional equivalent MAC in China's national market, there is an urgent need to provide essential data support for the sound formulation of the floor price. Meanwhile, the application of a carbon floor price policy is more complicated. To guide price-based climate policy design in China, other relevant policy issues, such as the quota allocation method, the expected growth rate of the floor price, the climatic and distributive effects of polices, deserve closer examination in future research.

CRediT authorship contribution statement

Chunli Zhang: Writing – original draft, Software, Data curation, Visualization, Methodology. **Ning Chang:** Writing – review & editing, Formal analysis, Supervision, Conceptualization.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2025.126599.

Data availability

Data will be made available on request.

References

Abrell, J., Rausch, S., Yonezawa, H., 2019. Higher price, lower costs? Minimum prices in the EU emissions trading scheme. Scand. J. Econ. 121, 446–481. https://doi.org/10.1111/sjoe.12279.

Brauneis, A., Mestel, R., Palan, S., 2013. Inducing low-carbon investment in the electric power industry through a price floor for emissions trading. Energy Policy 53. https://doi.org/10.1016/j.enpol.2012.10.048.

Cheng, J., Xu, L., Wang, H., Geng, Z., Wang, Y., 2022. How does the marginal abatement cost of CO_2 emissions evolve in Chinese cities? An analysis from the perspective of urban agglomerations. Sustain. Prod. Consum. 32, 147–159. https://doi.org/10.1016/j.spc.2022.04.013.

Dai, S., Zhou, X., Kuosmanen, T., 2020. Forward-looking assessment of the GHG abatement cost: application to China. Energy Econ. 88. https://doi.org/10.1016/j.eneco.2020.104758.

Fare, R., Grosskopf, S., Lovell, C.A.K., Yaisawarng, S., 1993. Derivation of shadow prices for undesirable outputs: a distance function approach. Rev. Econ. Stat. 75. https://www.jstor.org/stable/2109448.

Färe, R., Grosskopf, S., Noh, D.W., Weber, W., 2005. Characteristics of a polluting technology: theory and practice. J. Econom. 126. https://doi.org/10.1016/j.jeconom.2004.05.010.

Feng, C., Yuan, X., Wang, Q., Zhou, N., 2022. Implication of UK Carbon Price Floor Policy for China's Pricing Mechanism. Fiscal Science, pp. 152–160.

Goulder, L.H., Morgenstern, R.D., Burtraw, D., Karplus, V., Schreifels, J., Zhang, X., 2018. China's rate-based approach to reducing CO 2 emissions: strengths, limitations, and alternatives. AEA papers and Proceedings 108, 458–462. https://doi.org/10.1257/pandp.20181028.

Flachsland, C., Pahle, M., Burtraw, D., Edenhofer, O., Elkerbout, M., Fischer, C., Tietjen, O., Zetterberg, L., 2020. How to avoid history repeating itself: the case for an EU Emissions Trading System (EU ETS) price floor revisited. Clim. Policy 20 (1), 133–142. https://doi.org/10.1080/14693062.2019.1682494.

Goulder, L.H., Long, X., Lu, J., Morgenstern, R.D., 2022. China's unconventional nationwide CO2 emissions trading system: cost-effectiveness and distributional impacts. J. Environ. Econ. Manag. 111, 102561. https://doi.org/10.1016/j.jeem.2021.102561.

Gugler, K., Haxhimusa, A., Liebensteiner, M., 2023. Carbon pricing and emissions: causal effects of Britain's carbon tax. Energy Econ. 121, 106655. https://doi.org/10.1016/j.eneco.2023.106655.

Hailu, A., Ma, C., 2017. Estimating the cost of carbon abatement for China. New Directions in Productivity Measurement and Efficiency Analysis. Edward Elgar Publishing. https://doi.org/10.4337/9781786432421.00015.

He, X., 2015. Regional differences in China's CO_2 abatement cost. Energy Policy 80, 145–152. https://doi.org/10.1016/j.enpol.2015.01.044.

Hristu-Varsakelis, D., Karagianni, S., Pempetzoglou, M., Sfetsos, A., 2010. Optimizing production with energy and GHG emission constraints in Greece: an input-Output analysis. Energy Policy 38, 1566–1577. https://doi.org/10.1016/j.enpol.2009.11.040.

Ji, C.J., Wang, X., Wang, X.Y., Tang, B.J., 2024. Design and impact assessment of policies to overcome oversupply in China's national carbon market. J. Environ. Manag. 354, 120388. https://doi.org/10.1016/j.jenvman.2024.120388.

Kuosmanen, T., Zhou, X., 2021. Shadow prices and marginal abatement costs: convex quantile regression approach. Eur. J. Oper. Res. 289, 666–675. https://doi.org/10.1016/j.ejor.2020.07.036.

Leontief, W.W., 1986. Input-Output Analysis. Oxford University Press, New York.

Liu, L., Sun, X., Chen, C., Zhao, E., 2016. How will auctioning impact on the carbon emission abatement cost of electric power generation sector in China? Appl. Energy 168, 594–609. https://doi.org/10.1016/j.apenergy.2016.01.055.

Llop, M., 2020. Energy import costs in a flexible input-output price model. Resour. Energy Econ. 59. https://doi.org/10.1016/j.reseneeco.2019.101130.

Ma, C., Hailu, A., You, C., 2019. A critical review of distance function based economic research on China's marginal abatement cost of carbon dioxide emissions. Energy Econ. 84. https://doi.org/10.1016/j.eneco.2019.104533.

Ministry of Ecology and Environment, 2024a. Interim regulations on the management of carbon emission trading. https://www.mee.gov.cn/xxgk2018/xxgk/xxgk06/202103/W020210330371577301435.pdf.

Ministry of Ecology and Environment, 2024b. The total quota and allocation plan of the power generation industry in 2023 and 2024. https://www.gov.cn/zhengce/zhengceku/202410/P020241022275017526919.pdf.
Ministry of Ecology and Environment, 2024c. Work plan for the national carbon emission trading market to cover the cement, iron and steel and electrolytic aluminium industries (draft for comments). https://www.mee.gov.cn/xxgk2018/xxgk/xxgk06/202409/W020240909573354718696.pdf.
Mardones, C., Alvial, E., 2024. Evaluation of a carbon tax in Costa Rica linking a demand system focused on energy goods and an input-output model. Appl. Energy 363. https://doi.org/10.1016/j.apenergy.2024.123078.
Minihan, E.S., Wu, Z., 2012. Economic structure and strategies for greenhouse gas mitigation. Energy Econ. 34, 350–357. https://doi.org/10.1016/j.eneco.2011.05.011.
Mo, J., Tu, Q., Wang, J., 2023. Carbon pricing and enterprise productivity-The role of price stabilization mechanism. Energy Econ. 120, 106631. https://doi.org/10.1016/j.eneco.2023.106631.
Newbery, D.M., Reiner, D.M., Ritz, R.A., 2019. The political economy of a carbon price floor for power generation. Energy J. 40. https://doi.org/10.5547/01956574.40.1.dnew.
Ohlendorf, N., Flachsland, C., Nemet, G.F., Steckel, J.C., 2022. Carbon price floors and low-carbon investment: a survey of German firms. Energy Policy 169. https://doi.org/10.1016/j.enpol.2022.113187.
Peng, J., Yu, B.Y., Liao, H., Wei, Y.M., 2018. Marginal abatement costs of CO2 emissions in the thermal power sector: a regional empirical analysis from China. J. Clean. Prod. 171. https://doi.org/10.1016/j.jclepro.2017.09.242.
Philibert, C., 2009. Assessing the value of price caps and floors. Clim. Policy 9, 612–633. https://doi.org/10.3763/cpol.2008.0586.
Pizer, W.A., 2002. Combining price and quantity controls to mitigate global climate change. J. Publ. Econ. 409–434. https://doi.org/10.1016/S0047-2727(01)00118-9.
Roberts, M.J., Spence, M., 1976. Effluent charges and licenses under uncertainty. J. Publ. Econ. 5 (3–4), 193–208. https://doi.org/10.1016/0047-2727(76)90014-1.
RGGI, 2024. Design elements for regional allowance auctions under the regional greenhouse gas initiative. https://www.mass.gov/doc/rggi-auctiondesign20080317pdf/. (Accessed 5 November 2024).
Shan, H., 2008. Reestimating the capital stock of China:1952-2006. J Quantitative Technol Econ 25, 17–31.
Song, Y., Liu, T., Li, Y., Zhu, Y., Ye, B., 2022. Paths and policy adjustments for improving carbon-market liquidity in China. Energy Econ. 115, 106379. https://doi.org/10.1016/j.eneco.2022.106379.
Tang, B.J., Ji, C.J., Hu, Y.J., Tan, J.X., Wang, X.Y., 2020. Optimal carbon allowance price in China's carbon emission trading system: perspective from the multi-sectoral marginal abatement cost. J. Clean. Prod. 253. https://doi.org/10.1016/j.jclepro.2019.119945.
Wang, B., Pizer, W.A., Munnings, C., 2022. Price limits in a tradable performance standard. J. Environ. Econ. Manag. 116. https://doi.org/10.1016/j.jeem.2022.102742.
Wang, K., Che, L., Ma, C., Wei, Y.M., 2017. The shadow price of CO2 emissions in China's iron and steel industry. Sci. Total Environ. 598, 272–281. https://doi.org/10.1016/j.scitotenv.2017.04.089.
Wen, X., Yao, S., Sauer, J., 2022. Shadow prices and abatement cost of soil erosion in Shaanxi Province, China: convex expectile regression approach. Ecol. Econ. 201. https://doi.org/10.1016/j.ecolecon.2022.107569.
Weng, Y., Zhang, D., Lu, L., Zhang, X., 2018. A general equilibrium analysis of floor prices for China's national carbon emissions trading system. Clim. Policy 18, 60–70. https://doi.org/10.1080/14693062.2018.1464895.
Wu, L., Chen, Y., Feylizadeh, M.R., 2019. Study on the estimation, decomposition and application of China's provincial carbon marginal abatement costs. J. Clean. Prod. 207, 1007–1022. https://doi.org/10.1016/j.jclepro.2018.10.082.
Xiao, B., Niu, D., Wu, H., Wang, H., 2017. Marginal abatement cost of CO2 in China based on directional distance function: an industry perspective. Sustainability (Switzerland) 9 (1), 138. https://doi.org/10.3390/su9010138.
Yao, Y.F., Liang, Q.M., 2016. Approaches to carbon allowance allocation in China: a computable general equilibrium analysis. Nat. Hazards 84, 333–351. https://doi.org/10.1007/s11069-016-2352-7.
Zhang, J., Wu, G., Zhang, J., 2004. The estimation of China's provincial capital stock: 1952-2000. Econ. Res. J. 35–44.
Zhang, X., Hueng, C.J., Lemke, R.J., 2023. Using a price floor on carbon allowances to achieve emission reductions under uncertainty. Econ. Anal. Pol. 80, 1096–1110. https://doi.org/10.1016/j.eap.2023.10.002.
Zhang, X., Gan, D., Wang, Y., Liu, Y., Ge, J., Xie, R., 2020. The impact of price and revenue floors on carbon emission reduction investment by coal-fired power plants. Technol. Forecast. Soc. Change 154, 119961. https://doi.org/10.1016/j.techfore.2020.119961.
Zhang, Y.F., Harris, J.M., Li, J., 2018. China's carbon market: accelerating a green economy in China and reducing global emissions. Global Development and Environment Institute Working Paper, 18-01.