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Carbon price under heterogeneous policy scenarios: Formation mechanisms, modeling, and applications

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ABSTRACT

As an artificial market, the carbon price is strongly shaped by carbon-market policies. Consequently, understanding its formation mechanism is essential for evaluating policy impacts. However, current research has paid limited attention to carbon price formation mechanisms under heterogeneous policy scenarios. Drawing on the fundamental mechanisms of carbon-market operations, this study integrates allowance supply–demand with corporate marginal abatement costs into a unified framework to derive the theoretical carbon-price formation mechanism under heterogeneous policy scenarios. These mechanisms are formalized in a new computational model for theoretical carbon price(Only including coal-fired power plants) in the context of China. The analysis yields several findings. First, government price directly affects carbon price, whereas carbon allowance, allocation method, and the proportion of free allocation influence price indirectly by affecting the market-driven component. Second, under hybrid allocation scenarios, the free allocation ratio flexibly modulates carbon price; nevertheless, extreme values—either excessively high or low—undermine this adjustment effect. Third, actual emission reductions can exceed government targets under paid and hybrid allocation methods. Incorporating the marginal abatement costs of coal-fired power plants into the model results in a theoretical carbon price that exceeds the actual market level. This suggests that current allowance allocation are overly lenient, which keeps carbon price below the level of firms' true marginal abatement costs and fails to impose a binding constraint on emissions.

1. Introduction

Facing the severe challenge of global climate change, countries worldwide have proposed carbon neutrality goals. Achieving this ambitious objective requires innovation and refinement of policy instruments, among which the development of carbon market is widely regarded as a critical measure. As of 2024, 36 Carbon Trading Systems (CTSs) are operational globally, covering approximately 18% of global greenhouse gas emissions, involving nearly one-third of the world's population, and accounting for roughly 58% of global GDP (ICAP, 2024). Thus, carbon market have become a significant component of global climate governance, and their influence and coverage continue to expand.

However, carbon market continue to confront significant challenges related to policy selection during their development and operation. Determining appropriate allowance allocation methods, setting emission allowance volumes, and establishing government price levels remain difficult. Inappropriate policies can lead to carbon price that are too low to reflect the environmental costs of emissions accurately. Consequently, enterprises may lack sufficient incentives to engage in carbon market, leading to market stagnation. This undercuts corporate incentives for emission reduction and further compromises the effectiveness of carbon market in mitigating emissions.

To address these challenges, it is essential to clarify the carbon-price implications of heterogeneous carbon policies—allocation methods, government price, allowance volumes, and free allocation ratio. Carbon allowances and price constitute the core regulatory tools through which carbon market operate: allowances constrain corporate emissions, while pricing internalizes negative externalities and incentivizes reductions. Carbon price are determined by the market supply–demand dynamics

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for allowances, which are significantly influenced by carbon policies. Government implement carbon policies as combinations of heterogeneous measures, which makes price formation mechanisms particularly complex. Thus, elucidating how different policy instruments influence carbon price is a prerequisite for designing effective carbon policies. Currently, the mechanisms through which these policies affect carbon price remain unclear, leaving government without robust theoretical guidance when formulating policies.

To investigate the mechanisms through which carbon policies influence carbon price, this study employs a logical analysis grounded in the fundamental operations of the carbon market and market price theory. It details how the supply and demand of carbon allowances and corporate abatement costs influence carbon pricing under heterogeneous policy scenarios, elucidating the carbon price formation mechanism. Subsequently, these mechanisms are formalized into a framework, resulting in the development of a precise theoretical carbon pricing model. Finally, using production data from Chinese coal-fired power enterprises, the model is operationalized to calculate the theoretical carbon price(Only including coal-fired power plants) for China. The marginal contributions of this study are threefold. First, it adopts a perspective of carbon policy combinations rather than isolated policies. Second, it integrates carbon allowance supply–demand dynamics and corporate marginal abatement costs into carbon pricing. Third, it constructs a new theoretical carbon pricing model, offering new insights and methodologies for subsequent research.

2. Literature

Current research on the impact of heterogeneous carbon policies on price has primarily focused on allowance allocation methods, allowance volumes, and government price (Steinebach et al., 2021; Tang et al., 2020; Li et al., 2023; Ye et al., 2025). Studies on allocation methods have typically examined provinces, industries, or enterprises as subjects, comparing different allocation approaches by calculating marginal abatement costs under various scenarios, often using methods such as shadow pricing (Dominioni, 2022; Wen et al., 2022; Wang et al., 2024a, Wang et al., 2024b). These studies have concluded that paid allocation maximizes carbon price incentives, whereas free allocation minimizes them (Lin and Huang, 2022; Zhang et al., 2019a, 2019b). Additional research has examined variations in allocation standards within free-allocation schemes (e.g., grandfathering vs. benchmarking)—grandfathering based on historical emissions yields stronger carbon-price incentives (Zhang et al., 2015; Guo et al., 2023).

Research on the impact of allowance volumes on carbon price has employed system dynamics, threshold regression models, and supply chain models. Most studies have agreed that tightening allowances elevates carbon price (Song et al., 2022; Wang et al., 2023; Kaufman et al., 2020). Furthermore, stringent allowances and corresponding high price enhance the effectiveness of emission reduction (Xia et al., 2023; Zhang et al., 2018; Dai et al., 2018). Additional studies have analyzed stakeholders (e.g., governments, allowance suppliers, purchasers), highlighting the significant influence of the allowance-price correlation coefficient on market efficacy (Hao et al., 2023; Wang et al., 2018; Chen et al., 2023).

Studies on government price have used simulation and econometric models to explore its impact on carbon price. Notably, only sufficiently high government price can effectively incentivize carbon price and promote emission reduction (Tang et al., 2017; Chen and Lin, 2021; Gugler et al., 2021; Zhou et al., 2024). Conversely, excessively high pricing may disrupt carbon price and undermine reduction efficiency (Tang et al., 2020; Gavard et al., 2022; Guo et al., 2024), necessitating range restrictions to ensure price stability (Esmaeili Avval et al., 2022; Fridahl et al., 2024).

Existing research has separately examined the impact of allocation methods, allowance volumes, government price, and other carbon policies on carbon price; however, several aspects warrant further investigation. First, there is a lack of systematic research on carbon price formation mechanisms under different allowance allocation methods, leaving the carbon price formation mechanism without adequate theoretical underpinning. Second, most studies have evaluated single policies in isolation, although real-world carbon policies operate under heterogeneous policy combinations. Few studies have constructed policy combination scenarios to investigate price formation mechanisms systematically. Third, research calculating carbon price from corporate abatement costs has generally presented results as value ranges, lacking precise computational methods. Accordingly, a comprehensive framework that integrates carbon market policy, market supply-demand dynamics, and firm-level marginal abatement costs to derive a precise theoretical carbon price remains lacking. To address these gaps, this study adopts a comprehensive policy-combination perspective, incorporates allowance supply–demand dynamics and corporate abatement costs into a unified framework, analyzes carbon price formation mechanisms under heterogeneous policy combinations, and develops a computational model for theoretical carbon price.

3. Institutional background and theoretical model

3.1. Background and assumptions

Carbon market typically employ three allowance allocation methods: paid, free, and hybrid. This study examines these three prevalent real-world models. Under any allocation method, enterprises may obtain carbon allowances either directly from the government or through transactions with other firms. The market in which enterprises acquire allowances from the government is termed the primary market, and the acquisition price is defined as the government price (denoted S_1). The market in which firms obtain carbon allowances from other firms is termed the secondary carbon market. The price at which firms acquire carbon allowances in this market is called the market-driven price (denoted as S_2, which is not influenced by the government price S_1 but is jointly determined by market supply and demand, firms' marginal abatement costs, and other factors. It represents a function of the marginal abatement cost at the market equilibrium point across all firms and is endogenously determined by the policy parameters). Usually, enterprises procure allowances from the lower-priced source. The carbon price examined in this study refers to the equilibrium price in the secondary market when supply and demand are in balance. This price is influenced by the government price (S_1) and the market-driven price (S_2). To distinguish it from S_1 and S_2, we designate S as the final transaction price, i.e., the carbon price.

Based on real-world operations, we abstract the carbon market's emission reduction mechanism as follows. The government first announces carbon policies, setting key parameters including allocation methods, allowance volumes, and government price. Subsequently, under these policy constraints, enterprises make decisions on emission reduction or allowance purchases based on their abatement costs (where emission reduction refers to adjustments in production scale[1]). Through dynamic interactions, enterprises determine short-term production scales that satisfy carbon constraints, maximize profits, and minimize total abatement costs. Specifically, the government sets allowance allocations based on historical production-scale emissions, typically below historical levels to constrain emissions. Enterprises facing emission constraints have three choices: reduce emissions, obtain allowances in the primary market, or procure them in the secondary market. Enterprises follow profit-maximization principles—if their marginal emission reduction cost is lower than S_1 or S_2, they reduce emissions until

[1] Emission reduction can also be achieved by enhancing technological levels to reduce emissions per unit output under existing production scales. However, this study limits its analytical scope to the short term and does not consider technological progress.

marginal costs exceed S_1 and S_2, which allows them to purchase allowances. If $S_2 < S_1$, enterprises seek allowances in the secondary market, driving up S_2 until $S_2 > S_1$, prompting a shift to government purchases or emission reduction. When $S_2 < S_1$, enterprises buying from the government at fixed S_1 attempt to maximize purchases, but limited government supply eventually forces them to reduce emissions or seek secondary-market allowances. This cyclical process repeats until allowance supply-demand equilibrium stabilizes the final transaction price (S), allowing enterprises to establish production scales.

Additionally, we assume that the carbon market comprises n enterprises denoted $B_1, B_2, \ldots, B_n$, with initial production scales $L_1, L_2, \ldots, L_n$. Enterprises are ranked by increasing marginal emission reduction costs $R_1, R_2, \ldots, R_n$ (Blyth et al., 2009). Corporate emission reduction behavior reduces variable input, with marginal output decreasing as variable input declines. All enterprises have exact knowledge of their own marginal emission reduction costs. Emissions from enterprises in the carbon market are denoted as $E_1, E_2, \ldots, E_n$, summing to total emissions E. The government sets total allowances as a ratio e ($0 < e < 1$) of E, expressed as eE. Without loss of generality, under free allocation, allowances are distributed via grandfathering—proportional allocation based on historical emission levels—while under paid allocation, the government sells allowances at fixed price.

3.2. Carbon price formation mechanism under heterogeneous carbon policies

This study analyzes carbon price dynamics by examining enterprise decision-making under carbon policies and its impact on allowance supply-demand. Building on three allocation methods (free, paid, and hybrid allocation), we integrate policies incorporating allowance volumes, government price, and free allocation ratio to construct three policy scenarios and investigate their price formation mechanisms. To enhance clarity, we present the final results first (as shown in Fig. 1), followed by a detailed step-by-step explanation of their derivation.

Under free allocation, the final transaction price S is directly determined by the supply and demand of allowances in the carbon market, equaling the market-driven price S_2. Under paid allocation—when the emission reduction achieves the carbon allowance constraint—if $S_2 > S_1$, then S equals S_2; if $S_2 < S_1$, then S equals S_1. Under hybrid allocation—when the emission reduction achieves the carbon allowance constraint—if $S_2 > S_1$, then S equals S_2; if $S_2 < S_1$, then S equals S_1 with a small free allocation ratio, while S lies between S_1 and S_2 corresponding to the initial allowance volume eE with a large free carbon allowance ratio.

3.2.1. Free allocation

Under the free allocation method, the government distributes carbon allowances to enterprises at no cost, setting S_1 to 0. Enterprises first seek allowances from the government. Using grandfathering, enterprises receive allowances $eE_1, eE_2, \ldots, eE_n$, with total allowances being eE. After allocation, each enterprise still faces a allowance deficit and must choose to reduce emissions or seek allowances in the secondary carbon market.

1. Initially, with low S_2, no allowance transactions occur. This price represents what allowance-seeking enterprises are willing to pay to maximize profits or surplus, yet no enterprises sell allowances. Allowance supply falls far short of demand in the secondary market. S_2 rises rapidly until it exceeds the marginal emission reduction cost R_1 of enterprise B_1, prompting B_1 to reduce emissions.
2. When B_1's reduction reaches (1-e)E_1, it achieves compliance with the carbon allowance constraint. Although B_1's marginal emission reduction cost R_1 increases with further reductions, S_2 remains higher than R_1.[2] Even after compliance, B_1 continues reducing emissions and selling excess allowances in the secondary market to maximize profits.
3. B_1 persists until S_2 reaches the marginal cost R_2 of enterprise B_2, triggering B_2's emission reductions. This process repeats for B_3, B_4, and so on, until total reductions reach (1-e)E, achieving the carbon market's emission reduction target
4. At this equilibrium, all enterprises comply through reductions or trading, secondary market supply-demand balances, S_2 stabilizes, and S equals S_2. The process is illustrated in Fig. 2

3.2.2. Paid allocation

Under the paid carbon allowance allocation scheme, the government sells allowances to enterprises at a fixed price, which is S_1. S_1 represents the government's expectation of the emission reduction cost required to achieve carbon allowance compliance and must be greater than 0. If S_1 is less than the marginal emission reduction cost R_1 of enterprise B_1, enterprises will first obtain allowances from the government, and S will be consistent with the free allocation scenario. Therefore, this section focuses on scenarios where S_1 is relatively high.

Initially, S_2 is less than the marginal emission reduction cost R_1 of enterprise B_1, which is less than S_1. Enterprises seek allowances in the secondary carbon market. At this point, allowance supply falls far short of demand in the secondary market, causing S_2 to rise rapidly. Consistent with the free allocation scenario, enterprises reduce emissions until total reductions reach (1-e)E, achieving the emission reduction target. Two outcomes emerge: first, S_2 remains less than S_1; second, S_2 becomes greater than or equal to S_1.

1. When S_2 is less than S_1, despite the government holding substantial allowances, enterprises continue seeking allowances in the secondary market. S_2 continues to rise and enterprises persist in emission reduction. This continues until S_2 equals S_1, at which point enterprises purchase allowances from the government until their demand is satisfied. At this equilibrium, supply and demand balance in the secondary market and S equals S_1. This process is illustrated in Fig. 3.

2. When S_2 exceeds S_1, there must be a moment before achieving the emission reduction target when S_2 equals S_1. Subsequently, enterprises will purchase allowances from the government. Thus, enterprises obtain government-held allowances before reaching the emission reduction target. Nevertheless, as the emission reduction target remains unmet, enterprises continue seeking allowances in the secondary market until the emission reduction target is achieved. All enterprises satisfy their carbon allowance demands, secondary market supply-demand reaches equilibrium, and S equals S_2. This process is illustrated in Fig. 4.

3.2.3. Hybrid allocation

Under the hybrid allocation method, the government distributes part of carbon allowances freely and sells another part through fixed-price sales. Enterprises first obtain free allowances from the government; nonetheless, if their allowance requirements remain unmet, they continue seeking allowances from the government or the secondary

[2] If S_2 falls below its marginal emission reduction cost R_1, the enterprise ceases emission reduction, leaving R_1 unchanged. However, as allowance supply remains below demand in the secondary market, S_2 continues its upward trend. Consequently, S_2 eventually exceeds enterprise B_1's marginal emission reduction cost R_1.

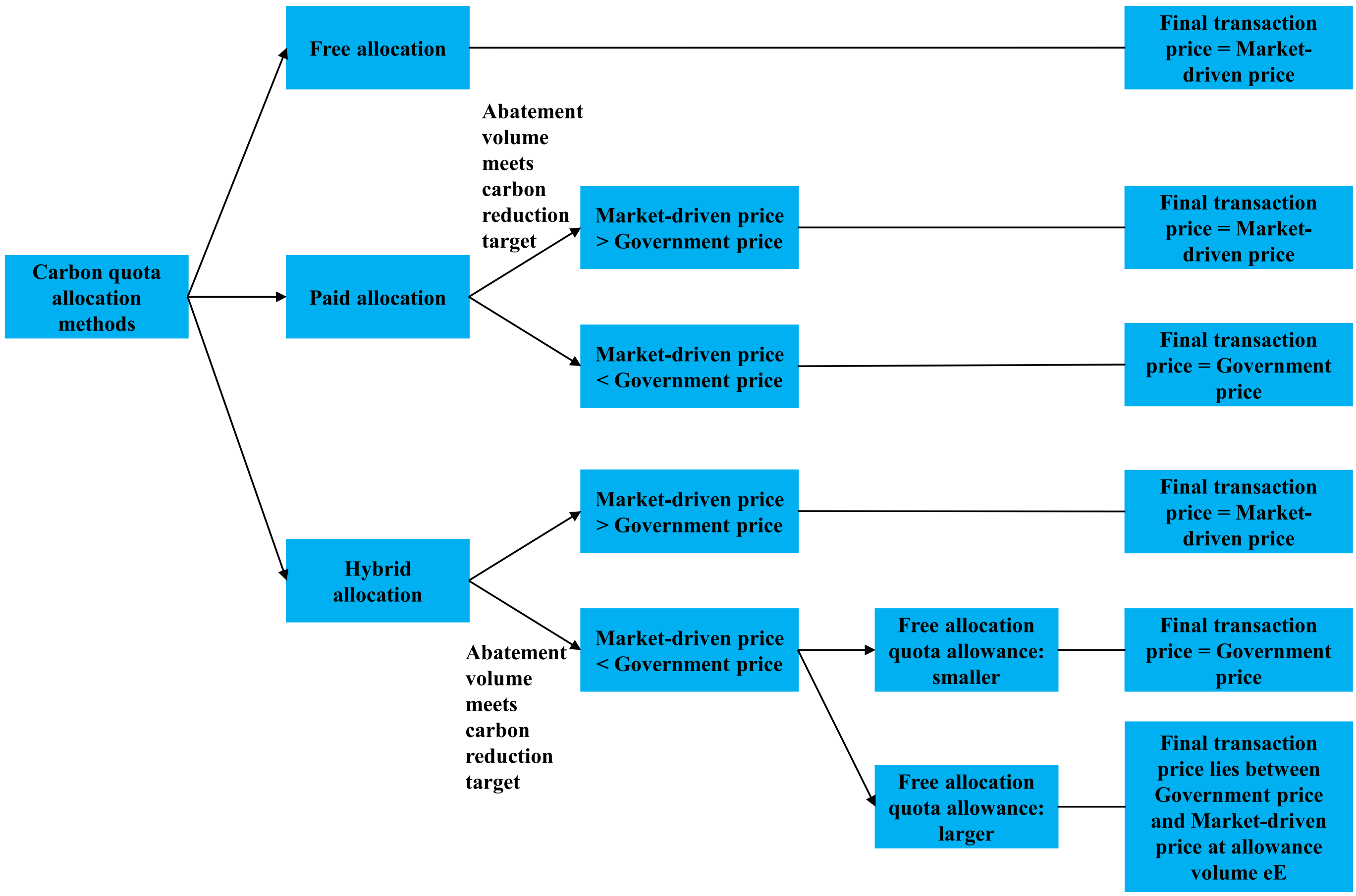

Fig. 1. Final transaction price under different allocation mechanisms.

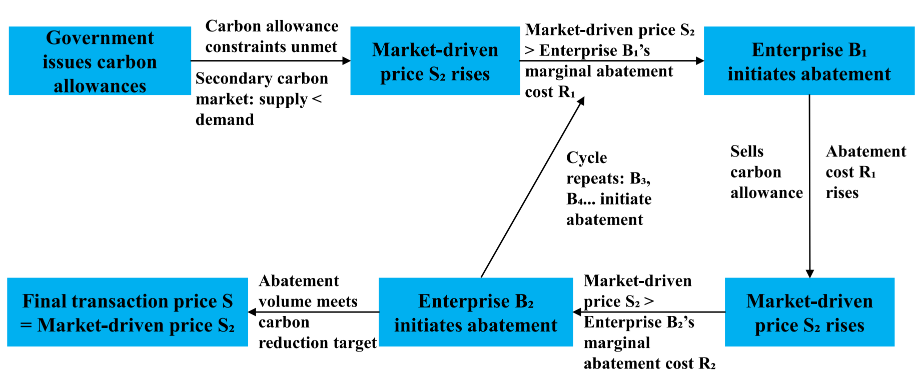

Fig. 2. Formation mechanism of the final transaction price under free allocation.

carbon market. Subsequent developments resemble the paid allocation scenario, splitting into two cases when the total emission reduction in the carbon market reaches (1-e)E: S_2 is greater than or equal to S_1, and S_2 is less than S_1. When $S_2 \geq S_1$, the final outcome aligns with the paid allocation scenario, and S equals S_2.

When the total emission reduction in the carbon market has reached (1-e)E and $S_2 < S_1$, two sub-scenarios emerge: one with a smaller free allocation ratio and another with a larger free allocation ratio. When the free allocation ratio is small, S matches the paid allocation scenario, with S equaling S_1.

Under the scenario with a high free allocation ratio, enterprises have already obtained substantial free allowances from the government and achieved the (1-e)E emission reduction target, leaving only a small deficit to meet the carbon allowance constraint. Enterprises continue seeking allowances in the secondary market, causing S_2 to rise, while enterprises persist in emission reduction. Owing to the small deficit, enterprises eliminate this gap through emission reductions before S_2 rises to S_1. Once enterprises satisfy their allowance requirements, S will exceed S_2 corresponding to the initial allowance volume eE but remain below S_1, as shown in Fig. 5.

3.3. Modeling the carbon Price formation mechanism

Based on the final transaction price formation mechanisms analyzed above, we derive:

Formula 1: Final transaction price under free allocation.

$S = S_2$ (1)

Formula 2: Final transaction price under paid allocation

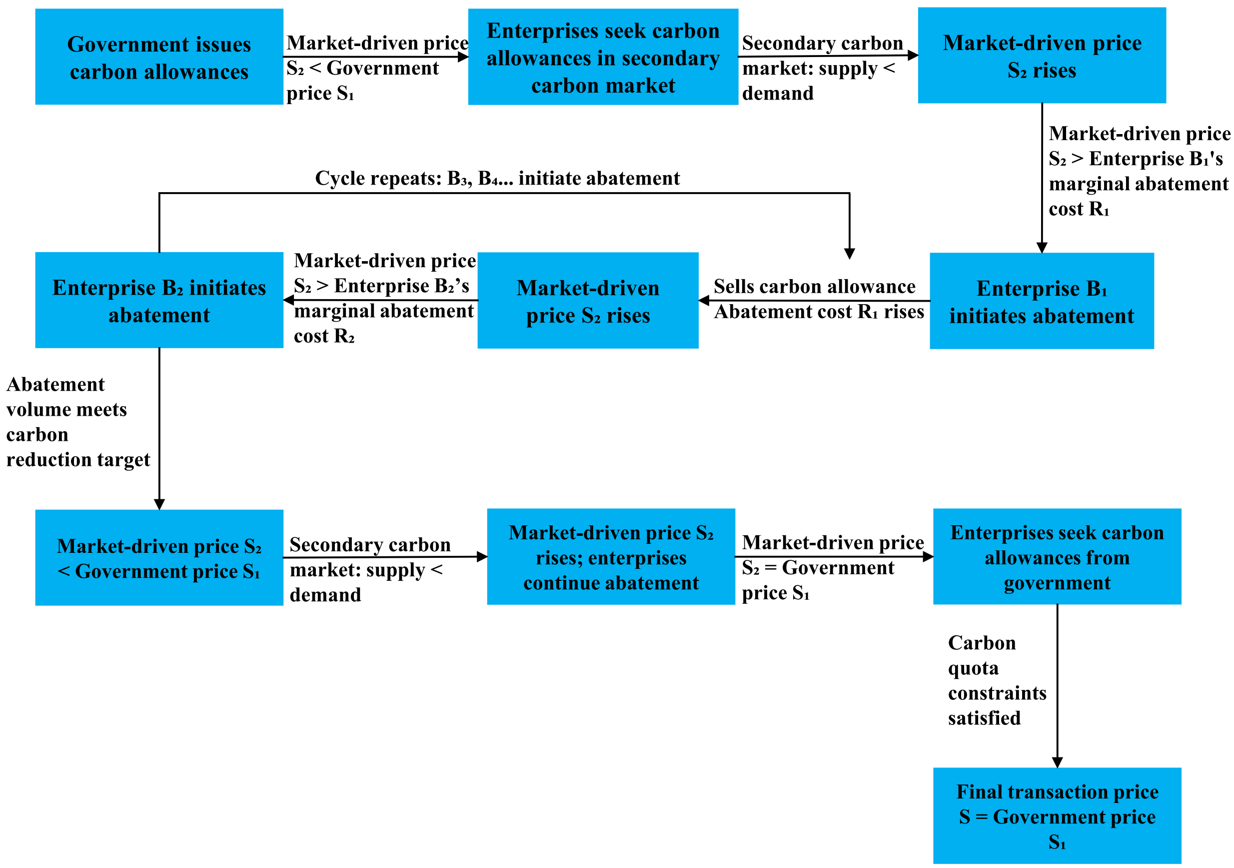

Fig. 3. Formation mechanism of the final transaction price under paid allocation when market-driven price S_2 < government price S_1.

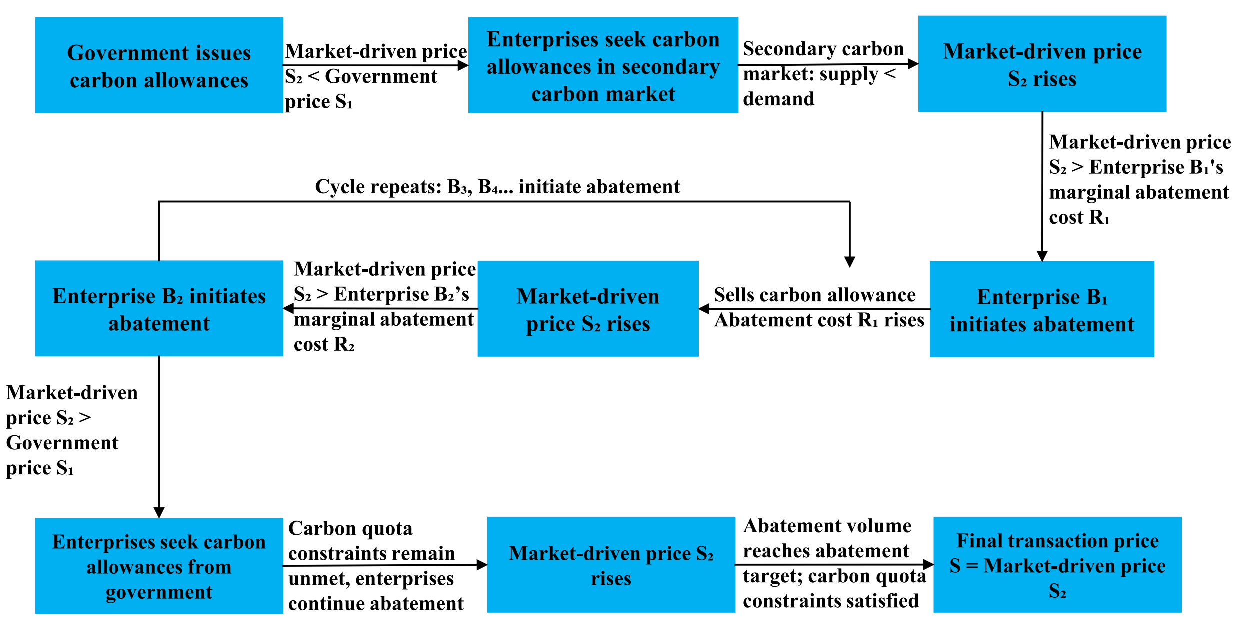

Fig. 4. Final transaction price formation mechanism under paid allocation when market-driven price S_2 > government price S_1.

$$S = \begin{cases} S_1, S_1 > S_2 \\ S_2, S_1 < S_2 \end{cases} \quad (2)$$

Formula 3: Final transaction price under hybrid allocation

$$S = \begin{cases} S_2, S_1 < S_2 \\ S_1, S_1 > S_2 \cap a < a' \\ S_3, S_1 > S_2 \cap a > a' \end{cases} \quad (3)$$

where S_1, S_2, and S_3 are defined as:

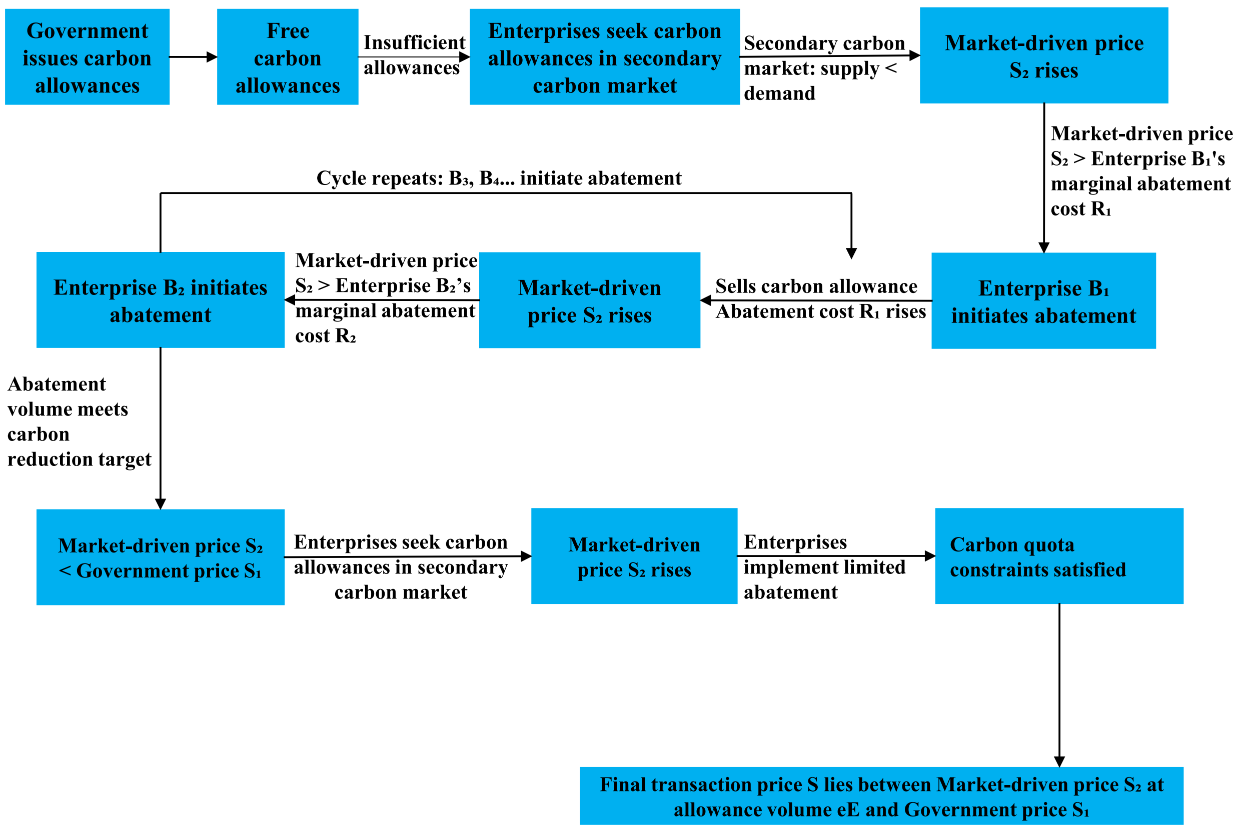

Fig. 5. Scenario with high free allocation ratio under hybrid allocation.

$$\begin{cases} S_1 = f_1(eE) \\ S_2 = f_2(eE) \\ S_3 = f_2(aeE) \end{cases} \tag{4}$$

Here, "S" is the final transaction price, "S_1" the government price, "S_2" the market-driven price, "S_3" the final transaction price between S_1 and S_2, "eE" the allowance volume, "a" the free allocation ratio under hybrid allocation, and "a'" the threshold value of a. Functions f_1 and f_2 represent the functional relationships between allowance volume and S_1/S_2. The computational procedures for S_1, S_2, and S_3 are detailed below.

3.3.1. Calculation method for government price S_1

The government price functions as a key exogenous variable, reflecting the government's targeted expectation for carbon pricing and performing a regulatory role in the market. Currently, China's carbon market is still in an early stage of development, characterized by a relatively low government price and an incomplete price regulation mechanism. In contrast, the European Union carbon market, as a representative mature international system, exhibits significantly higher carbon price, which represent the target level aspired to by China's carbon policy makers. Selecting the EU carbon price satisfies both the exogeneity requirement of the government price and the government's price expectations. Therefore, this paper sets the government price with reference to the price levels observed in the EU carbon market.

To align with the data period of corporate abatement costs, the 2022 carbon price data from the EU carbon market is first selected as the baseline value for the government price. Furthermore, since the government price reflects, to a certain extent, the government's expectations regarding carbon pricing, its value should gradually increase as the total carbon allowance tightens. Accordingly, this paper draws on previous research and adopts the projected EU carbon price for 2030 as the upper bound for the government price. Specifically, this paper adopts the EU carbon price of 656 CNY/ton in 2022 as the lower bound of the government price (corresponding to the scenario with 100% of the carbon allowance) and uses the projected EU carbon price of 1183 CNY/ton for 2030 from BNEF (2024) as the upper bound (corresponding to the scenario with 0% of the carbon allowance). Based on this, an inverse linear relationship between the government price and the carbon allowance is assumed, and the corresponding pricing formula is constructed as shown in Eq. (5). In addition, adjustments to the EU carbon price are conducted for sensitivity analysis, with details provided in the Appendix.

$$S_1 = f_1(eE) \tag{5}$$

3.3.2. Calculation method for market-driven price S_2

Since, under free allocation, the final transaction price S is equal to the Market-driven price S_2, it follows that the calculation of S_2 is based on the price formation mechanism of S, as outlined below. Based on the mechanism illustrated in Fig. 2, the calculation model for S_2 is constructed as follows. First, firms are ranked in an ascending order according to their marginal abatement costs. The firm with the smallest marginal abatement cost is denoted as B_1. The output of firm B_1 is gradually reduced, and the adjusted input-output data are substituted into the shadow price formula (Eq. (5) in the Appendix) until its marginal abatement cost equals that of the next firm, B_2 (denoted as R_2). At this point, the emission reduction achieved by firm B_1, denoted as E_1' and the corresponding marginal abatement cost R_2 are recorded.

If the cumulative emission reduction already meets the overall sectoral abatement target, the total emissions at this stage correspond to the total carbon allowance and the marginal abatement cost of firm B_1 (i.e., R_2) represents the market-driven price S_2. Consequently, the total carbon allowance and the market-driven price are shown in Eq. 6:

$$eE = E - E_1'$$

$$S_2 = R_2 \tag{6}$$

We obtained one set of data for total allowance volume and corresponding market-driven price. According to the theoretical model, enterprises B_1 and B_2 continue emission reductions, cycling through this process, obtaining multiple sets of data for total allowance volumes and market-driven price. Applying OLS regression to this data derives the functional relationship (f_2) between market-driven price and total allowance volume.

3.3.3. Final transaction price under hybrid allocation

This section focuses specifically on the scenario where, when total emission reductions reach (1-e)E: S_2 is lower than S_1 and the free allocation ratio is large. Assume free allocation volume is a·eE, paid allocation volume is b·eE, and a + b = 1. In this scenario: when the final transaction price has not yet matched S_1, enterprise allowance demands are already satisfied, and the paid allocation volume remains unused. Therefore, this scenario is equivalent to that of a free allocation scenario with allowance volume a·eE. The final transaction price is shown in Eq. 7:

$$S_3 = f_2(aeE) \tag{7}$$

4. Model application: China's theoretical carbon price(only including coal-fired power plants)

China, as the world's largest carbon-emitting economy, has its carbon market system construction critically significant for achieving national carbon neutrality goals and advancing global climate governance. Accurate measurement of theoretical carbon price is essential to ensure that the carbon market fulfills its emission reduction function. The theoretical model constructed in this study provides a method for precise calculation of theoretical carbon price. Applying this model to empirical research on China's carbon market helps understand the rationality of existing carbon pricing and offers scientific support for improving China's carbon market mechanisms.

This section first calculates marginal emission reduction costs for Chinese enterprises to meet the theoretical carbon price model's data requirements on corporate emission reduction costs. Subsequently, it inputs these costs into the carbon price calculation model to compute carbon price under free, paid, and hybrid allocation policy scenarios, followed by result analysis. It should be emphasized that this study focuses exclusively on coal-fired power plants as the research sample, and the calculated carbon price may not fully represent the carbon price in a multi-sector context.

4.1. Corporate emission reduction costs

This study uses the shadow pricing method (Wang et al., 2017) to calculate corporate marginal emission reduction costs (specific model functions see Appendix 1). The shadow price is the incremental cost of producing one additional unit of a product under given conditions while achieving optimal resource allocation. In recent years, carbon emission issues have attracted increasing attention from experts and scholars. Given its capacity to characterize the marginal costs faced by enterprises, the shadow pricing method has been widely applied in estimating the abatement cost of carbon dioxide. Specifically, the shadow price of carbon dioxide represents the output loss—or the economic cost of abatement—resulting from reducing one unit of CO_2 emissions. The directional distance function is currently the predominant model for calculating the shadow price of CO_2. Compared to methods like the market price approach or computable general equilibrium (CGE) modeling, the advantage of the directional distance function (DDF) lies in its ability to allow for a proportional increase in desirable outputs and decrease in undesirable outputs by setting a direction vector. This directly characterizes the technical feasibility of emission reduction for power plants, providing a natural theoretical framework for calculating abatement costs (shadow price). The DDF can simultaneously estimate a plant's environmental technical efficiency (i.e., its distance from the emission reduction frontier) and the shadow price on the frontier (i.e., the frontier's slope) in a single step. This ensures intrinsic consistency between efficiency assessment and cost estimation. In this study, economic output and carbon dioxide emissions are employed as the desirable and undesirable outputs of the model, measured by operating revenue and CO_2 emissions, respectively. Inputs include indicators such as installed capacity, energy consumption, and employment. The direction vector is set as $(g_y, -g_b) = (1, -1)$.

In terms of data selection, the coal-power sector is China's largest carbon-emitting industry and a primary participant in the carbon market. Coal-fired power enterprises significantly influence carbon price, thus appropriate as this study's research subject. Key indicators—installed capacity, energy consumption, number of employees, operating income, and CO_2 emissions—were selected as foundational data for calculating marginal emission reduction costs of coal-power enterprises.

This study comprehensively considered factors such as geographical distribution and installed capacity, selecting a sample of 300 coal-fired power plants nationwide. The installed capacity accounts for 31% of the national total for coal-fired power plants, providing a fairly comprehensive representation of the operational status of China's coal-fired power sector. In terms of geography, the sample ensures representation from each province. Regarding capacity scale, it also covers all types of generating units, guaranteeing the diversity and representativeness of the sample. To further validate the reliability of our findings, the results were compared with similar previous studies, showing that the calculated marginal abatement costs for coal-fired power plants in this study are largely consistent with earlier estimates.

Considering data completeness and accessibility, 2022 data were used for calculation. Among these, installed capacity, energy consumption, number of employees, and operating income data mainly originated from power enterprise annual reports, power generation bulletins, and social/environmental responsibility reports; CO_2 emissions data originated from the National Pollutant Permit Management Information Platform, ensuring data authority and accuracy. Inputting Chinese coal-power plant data into the shadow pricing method, this study ultimately obtained 2022 CO_2 shadow price for 300 Chinese coal-fired power enterprises. An observation of the shadow price of these 300 coal-fired power plants reveals that plant-level shadow price are distributed between 500 and 1308 CNY/ton (see Appendix 1 for detailed results).

4.2. Results of China's theoretical carbon price(only including coal-fired power plants)

We input corporate marginal emission reduction costs into the carbon price calculation model, obtaining theoretical carbon price under different scenarios.

4.2.1. Free allocation

Under free allocation, S equals S_2. Thus, deriving S_2 directly yields S. The functional relationship between allowance volume eE and S_2 is shown in Fig. 6. Additionally, this paper conducts robustness checks on the results. Detailed information is provided in the appendix.

After comprehensively comparing the fitting results of different functional forms, the quadratic functional form with the highest R^2 was ultimately selected for fitting. The achieved R^2 of 0.97 meets the requirements of this study. Fitting the shadow price into a smooth curve introduces only minor errors in the resulting values and does not affect the underlying model mechanism. Under free allocation, S_1 is 0, and final transaction price are solely influenced by free allocation methods and allowance volumes. From Fig. 6 it can be seen that under free allocation, S exhibits a negative correlation with allowance volume. At near 100% allowance volume, final transaction price is approximately 500 CNY/ton. Subsequently, as allowance volume gradually decreases,

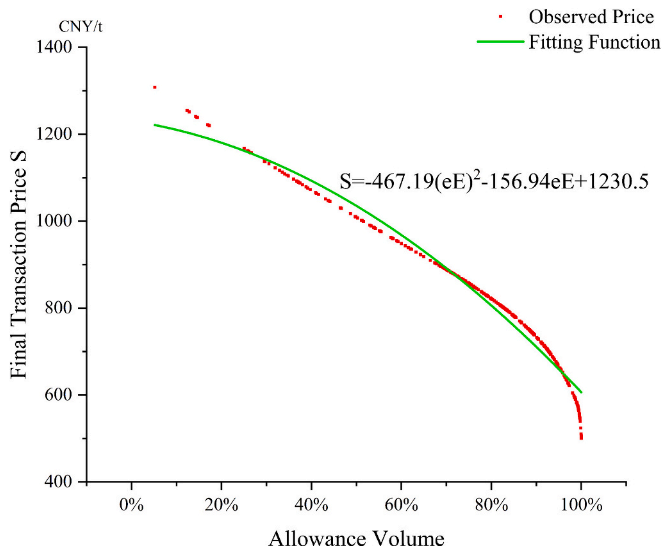

Fig. 6. Relationship between final transaction price and total allowance volume under free allocation.

the final transaction price gradually increases; at zero allowance volume, S is approximately 1230 CNY/ton. Of course, allowance volumes never reach such low levels in reality; this is only to illustrate final transaction price trends. Notably, the variation range of the final transaction price is close to the range of corporate marginal emission reduction costs.

4.2.2. Paid allocation

Based on the aforementioned relationship, the government price increases linearly with the carbon allowance, ranging from a lower bound of 656 CNY/ton to an upper bound of 1183 CNY/ton. The resulting government price is illustrated in Fig. 7.

Furthermore, simultaneously solving the government price function and market-driven price function yields Eq. 8:

$$\begin{cases} S_1 = 1183 - 527\text{eE} \\ S_2 = -467.19(eE)^2 - 156.94eE + 1230.5 \end{cases} \tag{8}$$

Solving this system produces:

$$e = 90.5\% \tag{9}$$

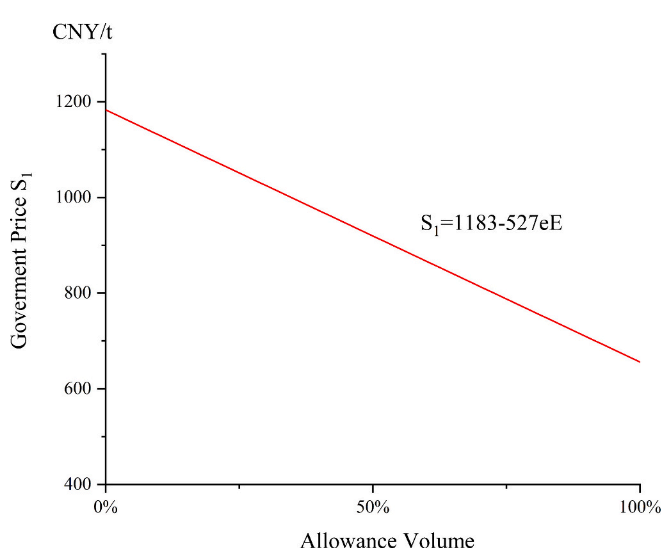

Fig. 7. Relationship between government price under paid allocation and total allowance volume.

Where e represent the allowance volume proportions at which S_2 equals S_1. This indicates that, based on the 2022 data from Chinese coal power plants, S_1 equals S_2 when the total allowance volume is 90.5%, respectively. When the total allowance volume exceeds 90.5%, S_1 is greater than S_2; consequently, the final transaction price S equals S_1. When the allowance volume is less than 90.5%, S_2 is greater than S_1; consequently, the final transaction price S equals S_2. Therefore, under paid allocation, the relationship between allowance volume eE and final transaction price S is given by Eq. 10 (Fig. 8):

$$S = \begin{cases} 1183 - 527eE \; e > 90.5\% \\ -467.19(eE)^2 - 156.94eE + 1230.5 \; \text{e} < 90.5\% \end{cases} \tag{10}$$

Fig. 8 demonstrates that under paid allocation, S exhibits a significant negative correlation with allowance volume eE. However, compared to the free allocation scenario, for the same allowance volume eE, the final transaction price under paid allocation is greater than or equal to that under free allocation. When the allowance volume exceeds 90.5%, the final transaction price under paid allocation is greater than under free allocation. When the allowance volume is less than 90.5%, the final transaction price under paid allocation equals that under free allocation.

4.2.3. Hybrid allocation

As described above, this section first considers the scenario where emission reductions meet expectations, S_2 is less than S_1, and the free allocation allowance is substantial. Under these conditions, the final transaction price can be expressed by Eq. 11:

$$S = -467.19(aeE)^2 - 156.94aeE + 1230.5 \tag{11}$$

Combining the preceding analysis, the final transaction price function under hybrid allocation is given by Eq. 12 (Fig. 9):

$$S = \begin{cases} 1183 - 527eE \; \text{e} > 90.5\% \cap a < a' \\ -467.19(aeE)^2 - 156.94aeE + 1230.5 \; \text{e} > 90.5\% \cap a > a' \\ -467.19(eE)^2 - 156.94eE + 1230.5 \; \text{e} < 90.5\% \end{cases} \tag{12}$$

We now proceed to solve for this threshold. According to the preceding analysis, when the total emission reduction reaches (1-e)E, the condition $S_2 < S_1$ holds, and S_2 increases with any further reduction. After an additional reduction of e'E is achieved, S_2 becomes equal to S_1. If the carbon market is precisely in an equilibrium state at this juncture, the free allocation ratio a is defined as the threshold a'. This leads to the establishment of Eq. (13):

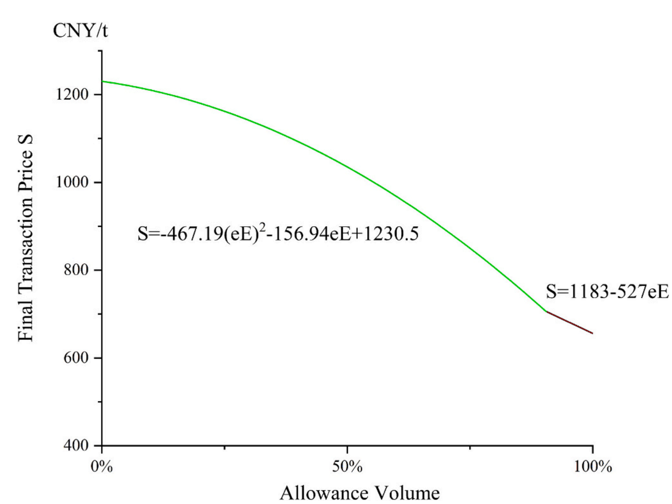

Fig. 8. Relationship between allowance volume and final transaction price under paid allocation.

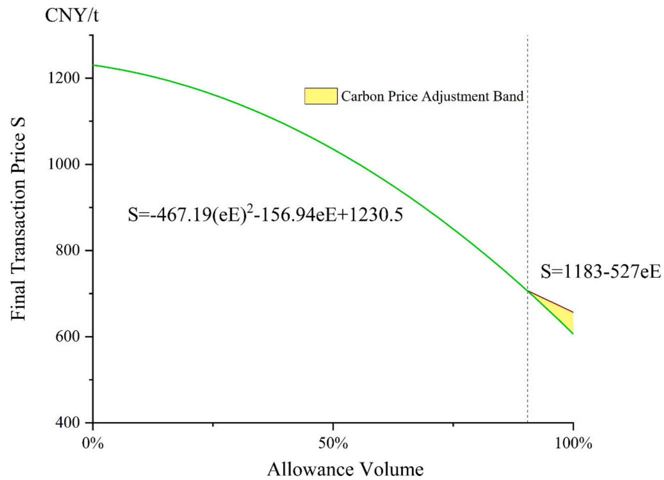

Fig. 9. Relationship between allowance volume and final transaction price under hybrid allocation.

$$(1-e)E + e'E + a'E = E \tag{13}$$

$$\text{Solve for}: a' = e - e' \tag{14}$$

The condition $S_2 = S_1$ leads to Eq. (15):

$$-467.19\left((e-e')E\right)^2 - 156.94(e-e')E + 1230.5 = 1183 - 527eE \tag{15}$$

Solving this system produces:

$$a' = \frac{\left(-156.94 \pm \sqrt{156.94^2 - 4 \times 467.19 \times (47.5 + 527e)}\right)}{934.38} \tag{16}$$

When the carbon allowance volume exceeds 90.5%, the threshold a' decreases as the allowance volume increases. This relationship depends on the price difference between S_1 and S_2 under varying levels of carbon allowance volume. The equation reveals that under hybrid allocation, when the allowance volume exceeds 90.5%, the final transaction price depends on the free allocation ratio. When $a > a'$ the final transaction price S varies between S_1 and S_2 as the proportion of free allocation allowance changes. Specifically, a larger proportion a of free allocation allowance brings S closer to S_2. When $a < a'$ S equals S_1.

5. Results analysis

The final transaction price of carbon allowances is jointly influenced by S_1 and S_2, essentially an outcome of the interaction between government regulation and market mechanisms. The pricing logic of the final transaction price can be decomposed into a dual mechanism: First, S_2 serves as a fundamental price signal, reflecting the impact of supply-demand dynamics for carbon allowances in the market and enterprises' abatement costs on carbon pricing. Second, S_1 mechanism establishes a price floor for market transactions by setting an intervention range, ensuring that the final transaction price does not fall below the policy-defined benchmark level.

Regarding the impact of the three allocation methods—free allocation, paid allocation, and hybrid allocation—on carbon price: Under the same allowance volume, the carbon price under paid allocation is greater than or equal to that under hybrid allocation, which is greater than or equal to that under free allocation. Under free allocation, enterprises' behavioral decisions depend solely on the carbon price and their own marginal abatement costs. Enterprises decide whether to reduce emissions or purchase allowances based on the carbon price and their abatement costs. Thus, when the supply and demand of carbon market reach equilibrium, the carbon price equals enterprises' marginal abatement costs, precisely matching S_2. Free allocation imposes fewer policy constraints and lower abatement pressure on enterprises, making it more acceptable, but it results in a lower carbon price.

Under paid allocation, enterprises' decisions are influenced by the carbon price and their marginal abatement costs, as well as S_1. Beyond purchasing allowances from other enterprises, enterprises may also buy from the government. Decisions require comparing the carbon price, marginal abatement costs, and S_1. Two outcomes emerge: when total abatement meets the target and S_1 is greater than S_2, the carbon price equals S_1; when S_1 is less than S_2, the carbon price equals S_2. Thus, the carbon price always equals the higher value. When S_2 is higher, the carbon market is sufficiently active, enabling it to drive abatement. When S_2 is lower, market mechanisms struggle to raise the carbon price, while S_1 ensures a price floor, preventing excessively low price. Paid allocation strictly limits the carbon price floor, better incentivizing abatement. However, enterprises face greater abatement pressure and reduced voluntary participation incentives.

Under hybrid allocation, the carbon price is further influenced by the proportion of free allocation allowance (a). When total abatement meets the target, S_1 is greater than S_2, and when a is large, the carbon price lies between S_2 and S_1, flexibly adjustable via a. This occurs because substantial free allocation allowance have entered the market, leaving the government with only a small portion of paid allowances. When abatement targets are met and S_1 is greater than S_2, enterprises seek allowances in the secondary carbon market, driving up S_2 and inducing further abatement. The entire market requires only minimal additional abatement to satisfy allowance constraints—insufficient to raise S_2 to the level of S_1. Thus, carbon price settles between the two. Hybrid allocation yields intermediate carbon price and abatement pressure between paid and free allocation, while allowing flexible price adjustment via a. Nevertheless, proportion of free allocation allowances must be carefully managed; values too high or too low negate its flexibility.

Furthermore, analysis reveals scenarios under paid allocation and hybrid allocation where actual abatement exceeds expected abatement. When the government sets an allowance volume of eE, the expected abatement is $(1-e)E$. Under free allocation, actual abatement equals expected abatement $(1-e)E$ when the market reaches equilibrium. Under paid allocation, when abatement reaches $(1-e)E$, if S_2 is less than S_1, then enterprises continue purchasing allowances from others. This creates a supply-demand imbalance in the secondary market, raising the carbon price and inducing further abatement until the carbon price equals S_1. Thus, actual abatement exceeds $(1-e)E$ if S_1 is high. Hybrid allocation exhibits the same behavior: when abatement reaches $(1-e)E$ and S_1 is greater than S_2, enterprises must abate further to satisfy allowance demand, regardless of a. This indicates that paid allocation and hybrid allocation better incentivize abatement. However, improper implementation may cause excessive abatement, disrupting long-term government planning and market control. Excessively high S_1 may also overburden enterprises, reducing participation incentives or causing financial distress.

Comparing the three methods: free allocation yields the lowest carbon price; paid allocation yields the highest carbon price, best incentivizing abatement; and hybrid allocation allows flexible carbon price adjustment based on practical needs and policy goals. While free allocation minimizes enterprise pressure and enhances market acceptability, it results in the lowest carbon price.

Finally, the calculation results for China's theoretical carbon price (Only including coal-fired power plants) indicate a significant divergence from the observed carbon price, with the former substantially exceeding the latter. This study identifies the following as the primary underlying reasons:

First, the stringency of policy constraints in the model is fundamentally defined by exogenous parameters—the total carbon allowance and the free allocation ratio. To ensure a smooth market transition, current policies have set a relatively lenient total allowance and primarily rely on free allocation. This not only directly results in the government price, as defined by the model, being at the lower end of its theoretical range but, more critically, influences the equilibrium price formation mechanism by altering the initial market endowment. A high proportion of freely allocated allowances injects a substantial volume of zero-cost allowances into the market during the initial distribution phase, significantly reducing the necessity for firms to acquire paid allowances through either the primary or secondary market. In the model, this is equivalent to exogenously increasing the "effective supply" in the secondary market, causing the market clearing condition to be met at a lower marginal abatement cost curve. Consequently, the final carbon price determined through the equilibrium mechanism is considerably lower than the theoretical value under a scenario with stringent allowances and paid allocation.

Second, the model deduces corporate behavior based on the cost-minimization principle, with the implicit premise that the cost of non-compliance is sufficiently high to make compliance the only rational choice. However, in reality, the perceived cost of non-compliance for firms—including economic penalties and reputational damage—remains relatively low. When the potential carbon price derived from the model exceeds this threshold, from a pure cost-benefit perspective, choosing non-compliance over purchasing allowances or investing in emission reduction becomes the dominant strategy. This fundamentally undermines market demand for high-priced allowances, preventing the price from converging toward the true marginal abatement cost. Furthermore, the ongoing development of the Monitoring, Reporting, and Verification (MRV) system further reduces the probability of non-compliant behavior being detected and penalized in practice. This effectively lowers the "effective cost of non-compliance" in corporate decision-making, thereby reinforcing firms' incentives to avoid compliance.

Third, foundational capabilities in data, monitoring, reporting, and verification, and regulatory oversight require substantial enhancement. Accurate estimation of a theoretical carbon price is contingent upon high-quality, firm-level data for both emissions and abatement costs. Presently, China lacks an official, systematic, and comparable statistical framework for marginal abatement costs. Simultaneously, regulatory capacity is still under development, resulting in insufficient deterrence against data misreporting and violations of compliance rules. These shortcomings highlight the significant infrastructural challenges confronting the carbon market as a precision economic policy tool, essential for its robust and effective operation.

6. Limitations and conclusions

6.1. Limitations

This study acknowledges the following limitations. First, the research focuses solely on coal-fired power plants and may not fully represent the carbon price dynamics of a nationwide carbon market encompassing multiple sectors. Second, the model specification omits certain secondary factors such as lack of liquidity, policy uncertainty, and avoidance behavior. Third, using the firms' marginal abatement cost to define government pricing blurs the distinction between exogenous policy choices and endogenous economic outcomes.

6.2. Discussion

This study clarifies the fundamental operating mechanisms of carbon market and analyzes carbon price formation under three scenarios: free allocation, paid allocation, and hybrid allocation. Based on this, we propose a method for calculating theoretical carbon price that models the relationship between carbon policies and carbon pricing. Finally, the model is applied to calculate China's theoretical carbon price(Only including coal-fired power plants), identifying problems in the carbon market and proposing improvement suggestions. We derive the following core conclusions:

First, the final transaction price of carbon allowances is jointly influenced by the government price and market-driven price. The market-driven price itself is affected by the carbon allowance allocation methods and the total allowance volumes. Under hybrid allocation, the proportion of free allocation allowances plays a flexible regulatory role in adjusting carbon price. Thus, carbon pricing outcomes vary under different allocation modes. Under paid allocation, if the market-driven price is greater than the government price, the carbon price equals the former. Conversely, if the market-driven price is lower than the government price, the carbon price equals the latter. Under hybrid allocation, if the market-driven price is greater than the government price, the carbon price equals the former; if the market-driven price is lower than the government price, the carbon price equals the latter when free allocation allowances are limited, but lies between the government price and market-driven price when free allocation allowances are abundant. The proportion of free allocation must remain within an appropriate range; otherwise, it loses its regulatory function. Under free allocation, the carbon price is directly determined by the supply and demand of carbon allowances in the market, equaling the market-driven price.

Second, when paid allocation or hybrid allocation is adopted, actual emission reductions may exceed policy expectations. Excessively high government price can incentivize firms to achieve reductions beyond targeted levels. While this strengthens abatement incentives, it may also lead to multifaceted complexities: first, the extent of over-compliance is difficult to predict and control precisely, which could disrupt the government's long-term emission reduction planning; second, it imposes unexpected compliance costs and operational pressure on firms; third, in responding to rising costs, firms may adjust production, investment, or location decisions to maintain competitiveness. In the absence of globally coordinated regulation, this could theoretically lead to carbon leakage, whereby emissions shift to regions with less stringent regulations.

Third, in China, the theoretical carbon trading price that reflects the true marginal abatement cost of firms—and thus could drive corporate emission reduction decisions—is significantly higher than the actual market price (by more than fivefold). The core reasons for this gap are as follows. First, the actual carbon allowance cap in China has been set relatively leniently, resulting in a long-term oversupply in the carbon market. This undermines the price discovery mechanism and prevents carbon price from serving as accurate cost signals. Second, the current reliance on free allocation restricts the government's ability to use paid allocation to establish an effective price floor and stabilize market expectations, weakening the carbon market's role as a binding constraint on corporate emissions. Furthermore, if policymakers rapidly tighten the allowance cap or significantly raise the government price to bridge this gap—without implementing supporting measures—it could, in the short term, increase corporate cost burdens, affect industrial competitiveness, and raise the risk of carbon leakage.

Policy implications are as follows.

First, transitioning from free to hybrid and paid allocation requires a calibrated and phased approach. While shifting allocation methods can enhance carbon market effectiveness, the pace and design of this transition must account for economic and sectoral readiness. Abrupt changes may increase compliance costs and affect the competitiveness of trade-exposed industries, potentially leading to carbon leakage. Therefore, government should consider a gradual pathway. In the first phase, the system is characterized by a high proportion of free allocation and a relatively lenient total carbon allowance volume, aimed at lowering market entry barriers and expanding coverage. During this phase, the government price is set at a relatively low level to cultivate market development. The second phase transitions toward a hybrid allocation model by introducing and gradually increasing the share of paid allocation. Through systematically reducing the free allocation ratio and moderately tightening the total carbon allowance volume, the supply of "zero-cost allowances" in the secondary market is substantially decreased, thereby lifting the market-driven price. Concurrently, the government price can be dynamically raised to establish a clear and progressively increasing price floor expectation. The third phase involves further tightening the total allowance volume and continuing to reduce the proportion of free allocation until it is phased out. The government price should be elevated to a level that clearly reflects long-term emission reduction targets and the social cost of carbon. The fourth phase establishes a market structure dominated by paid allocation, featuring stringent constraints on the total allowance volume and robust price signals. This enables the carbon price to serve as the core economic lever for achieving carbon neutrality goals.

Second, implementing hybrid or paid allocation necessitates proactive management of over-compliance risks. When actual emission reductions exceed targets—often due to high government price or stringent caps—this can undermine the predictability of long-term decarbonization pathways and create unintended compliance burdens. To mitigate this, policymakers should employ forward-looking modeling and regular market scans to track marginal abatement cost dynamics. Before adopting or adjusting hybrid/paid systems, stakeholder consultations and pilot studies can help gauge sectoral responses. Furthermore, rather than setting static government price and free allocation ratio, regulators could design adaptive mechanisms that allow for periodic review and adjustment based on observed market outcomes, such as predefined price corridors or allowance reserve triggers. This would help maintain incentive consistency while reducing planning uncertainty for firms.

Third, strengthening the data foundation is a fundamental long-term prerequisite for optimizing carbon market governance and price discovery. A deep-seated cause of the distorted price signal in China's current carbon market is the government's lack of access to high-quality, real-time, and comparable firm-level marginal abatement cost data, making it difficult to calibrate policies based on genuine abatement costs. Consequently, enhancing the statistical reporting, verification, and database development for corporate carbon emissions and cost data constitutes a critical foundational task. This involves establishing a unified monitoring, reporting, and verification system and exploring the development of an official mechanism for estimating and publishing marginal abatement costs. The long-term significance of this effort is twofold: on one hand, it provides a scientific basis for the government to dynamically adjust core parameters such as the total allowance cap and government price, making carbon policy more responsive; on the other hand, transparent and reliable cost data can itself enhance market expectations, improve price discovery, and ultimately steer carbon price toward convergence with the true social cost of abatement.

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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.

Appendix A. Calculation of enterprise marginal abatement costs

A.1. Shadow pricing method

Regarding the choice of functional form for the directional distance function, the options are as follows. Directional distance functions can be estimated via non-parametric Data Envelopment Analysis (DEA), parametric Stochastic Frontier Analysis (SFA), or parametric Linear Programming (LP). The DEA model, a non-parametric approach, does not require specifying a functional form for the distance function. However, DEA cannot guarantee the "existence" of shadow price and yields "non-unique" results. Parametric SFA uses econometric models to estimate the distance function, capturing impacts of stochastic shocks and technical inefficiency on the environmental output frontier while ensuring differentiability. Nevertheless, econometric models cannot predefine technological constraints, requiring ex-post evaluation of whether shadow price satisfy relevant conditions. Parametric LP constructs a flexible, twice-differentiable function to approximate the unknown production frontier, estimates parameters from data, and derives shadow price. The parametric approach guarantees "existence" and "uniqueness" of shadow price, allows flexible constraint setting, and is currently the most widely adopted method. Parametric LP models include the translog function and quadratic function forms. The translog function typically treats desirable and undesirable outputs symmetrically (expanding or reducing both simultaneously), which contradicts environmental regulation objectives. The quadratic function resolves this limitation while satisfying the translation property, twice-differentiability, and flexibility of directional distance functions. Theoretical studies confirm the superiority of the quadratic form under various conditions. Therefore, this study selects the quadratic function within the parametric LP framework to calculate shadow price.

The directional distance function is defined as Eq. A1:

$$D\left(x, y, b; g_y, -g_b\right) = \max\beta : \left(y + \beta g_y, b - \beta g_b\right) \in P(x) \tag{A1}$$

Here, y denotes desirable output (economic benefits in this study), b denotes undesirable output (CO_2 emissions), and P(x) = (y, b) represents all feasible production sets. The value of the directional distance function indicates: if current production is on the production possibility frontier, the value is 0; otherwise, it reflects the maximum unit β by which desirable output can increase by g_y units while undesirable output decreases by g_b units. ($y + \beta g_y$, $b - \beta g_b$) represents the optimal output under given inputs.

Let *R* denote the maximum revenue achievable under production feasibility constraints, as Eq. A2:

$$R(x, y, b) = \max py - qb; D\left(x, y, b; g_y, -g_b\right) \geq 0 \tag{A2}$$

where p is the price of desirable output and q is the price of undesirable output. Setting (g_y $-g_b$) = (1, −1) implies symmetric expansion of desirable output and reduction of undesirable output. Using the Lagrange multiplier method to maximize revenue yields Eq. A3:

$$\begin{cases} (p+q)\dfrac{\partial D(x, y, b; 1, -1)}{\partial y} = -p \\ (p+q)\dfrac{\partial D(x, y, b; 1, -1)}{\partial b} = q \end{cases} \tag{A3}$$

Taking the ratio gives Eq. A4:

$$-\frac{q}{p}=\frac{\partial D/\partial b}{\partial D/\partial y} \tag{A4}$$

The shadow price is expressed as Eq. A5:

$$q=-p\frac{\partial D/\partial y}{\partial D/\partial b}=-p\frac{\gamma_1+\gamma_2 b+\varepsilon_1 x_1+\varepsilon_2 x_2+\varepsilon_3 x_3+\mu y}{\beta_1+\beta_2 y+\delta_1 x_1+\delta_2 x_2+\delta_3 x_3+\mu b} \tag{A5}$$

The specific quadratic function is given in Eq. 6:

$$\overrightarrow{D}(x,y,b,g)=\alpha_0+\sum_{n=1}^{3}\alpha_n x_n+\beta_1 y+\gamma_1 b+\frac{1}{2}\sum_{n=1}^{3}\sum_{n'=1}^{3}\alpha_{nn'}x_n x_{n'}+\frac{1}{2}\beta_2 y^2+\frac{1}{2}\gamma_2 b^2+\sum_{n=1}^{3}\delta_n x_n y+\sum_{n=1}^{3}\varepsilon_n x_n b+\mu yb \tag{A6}$$

To derive shadow price, the parameters in the above equation must be estimated. This study employs a linear programming approach to solve for these parameters. Assuming power plants operate as closely as possible to the production frontier, the objective function of the linear programming model minimizes the sum of quadratic production functions across all plants, as expressed in Eq. 7:

$$Min\sum_{k=1}^{m}\overrightarrow{D}\left(x_k,y_k,b_k,g\right)$$

$$s.t.\begin{cases}1.\overrightarrow{D}(x_k,y_k,b_k,g)\geq 0;k=1,2\ldots m;\\2.\frac{\partial\overrightarrow{D}(x_k,y_k,b_k,g)}{\partial y}\leq 0;k=1,2\ldots m\ ;\\3.\frac{\partial\overrightarrow{D}(x_k,y_k,b_k,g)}{\partial b}\geq 0;k=1,2\ldots m\ ;\\4.\frac{\partial\overrightarrow{D}(x_k,y_k,b_k,g)}{\partial x_k^n}\geq 0;k=1,2\ldots m,n=1,2,3;\\5.\beta_1-\gamma_1=-1,\beta_2=\gamma_2=\mu,\varepsilon_n=\delta_n;n=1,2,3\\6.\alpha_{nn'}=\alpha_{n'n};n,n'=1,2,3\end{cases} \tag{A7}$$

The constraints carry the following meanings:Constraint 1 ensures all decision units lie on or within the production technology frontier, satisfying the non-negativity requirement of the directional distance function. Constraints 2 and 3 enforce monotonicity: desirable output exhibits monotonically decreasing effects on the distance function (i.e., increasing desirable output decreases the distance function value, ceteris paribus), while undesirable output shows monotonically increasing effects. Similarly, Constraint 4 ensures monotonically increasing effects for inputs. Constraints 5 and 6 represent the translation property and symmetry of the directional distance function, respectively.

A.2. Calculation results

Through computation, this study ultimately obtained the carbon dioxide shadow price for 300 coal-fired power plants in China for 2022. Analysis of these shadow price reveals a distribution ranging from 500 to 1308 CNY/ton across the plants. The outcomes show broad agreement with earlier research (Zhang and Liu, 2019; Du and Mao, 2015; Nakaishi, 2021), thereby supporting the reliability of this study's findings. After sorting the shadow price in ascending order, the data exhibits a uniform upward trend without sharp increases. This indicates strong sample diversity, encompassing coal-fired power plants under various production scenarios, thereby effectively representing the carbon dioxide shadow price across China's coal power industry. The results are illustrated in Fig. A1.

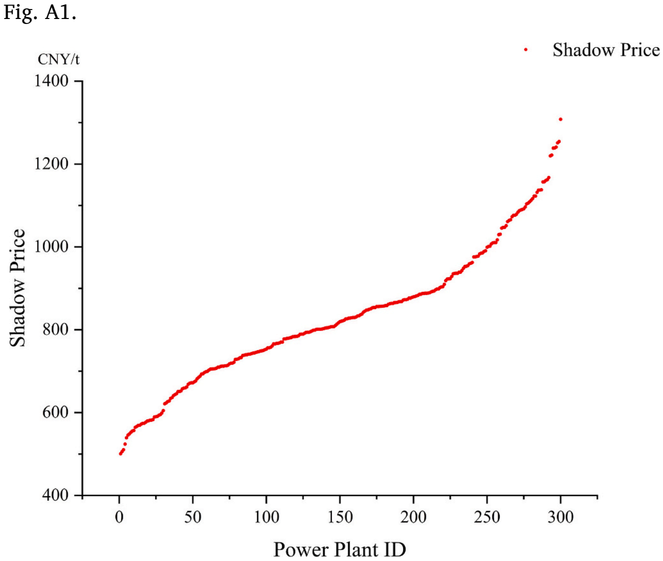

Fig. A1 Shadow price of CO_2 for China's coal-fired power plants.

A.3. Robustness

A random selection of 100 firms from the sample constituted the sub-sample, for which the market-driven price. The results are presented in Fig. A2.

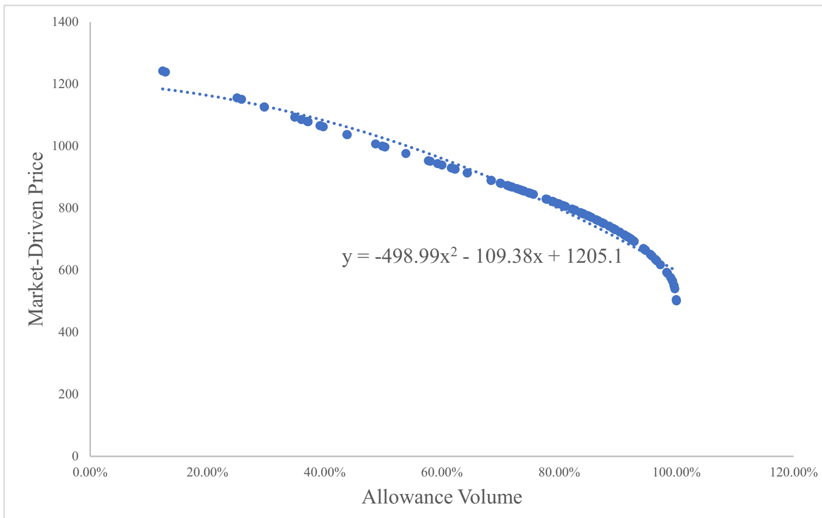

Fig. A2: The calculation results of the Market-Driven Price for the sub-sample.

Comparisons were made at several key points, with the results detailed in Table A1.

Table A1: The comparison of market-driven price.

Allowance Volume	Total sample	Sub-sample	Difference
90%	711	702	1.18%
80%	806	798	0.96%
70%	892	884	0.86%
60%	968	960	0.86%
50%	1035	1026	0.92%

It can be observed that the difference between the key points of the sub-sample and the total sample is within 5%, thereby confirming the robustness of the findings.

A.4. The underlying data used for the fitting

Table A2: Carbon allowance volume and market-driven price.

Allowance Volume	Market-driven Price	Allowance Volume	Market-driven Price	Allowance Volume	Market-driven Price	Allowance Volume	Market-driven Price
100.00%	501	91.26%	719	80.11%	821	63.27%	929
99.99%	506	91.23%	720	79.98%	822	62.25%	935
99.97%	510	91.07%	721	79.78%	823	62.07%	936
99.89%	524	90.45%	728	79.34%	826	62.04%	936
99.77%	539	90.42%	729	79.33%	826	62.03%	936
99.70%	546	90.32%	730	79.14%	828	61.59%	939
99.67%	549	90.12%	732	79.09%	828	61.56%	939
99.62%	553	90.06%	733	78.96%	829	60.87%	943
99.58%	556	89.61%	738	78.89%	830	59.99%	949
99.56%	557	89.54%	739	78.88%	830	59.26%	953
99.44%	564	89.43%	740	78.75%	831	59.17%	953
99.40%	567	89.41%	740	78.42%	833	58.97%	955
99.35%	569	89.32%	741	78.28%	834	58.19%	959
99.34%	570	89.27%	741	77.96%	836	58.01%	960
99.27%	572	89.16%	743	77.73%	838	57.69%	962
99.23%	574	89.05%	744	77.10%	842	55.49%	976

(continued on next page)

(*continued*)

Allowance Volume	Market-driven Price	Allowance Volume	Market-driven Price	Allowance Volume	Market-driven Price	Allowance Volume	Market-driven Price
99.22%	574	89.00%	744	76.71%	845	55.42%	976
99.16%	577	88.90%	745	76.41%	847	55.32%	977
99.08%	579	88.77%	747	76.30%	848	55.17%	978
99.05%	580	88.71%	747	76.10%	849	54.26%	983
99.01%	582	88.57%	749	75.92%	851	53.97%	985
99.00%	582	88.51%	749	75.59%	853	53.85%	986
98.95%	583	88.45%	750	75.49%	854	53.27%	989
98.74%	589	88.23%	752	75.47%	854	53.02%	991
98.70%	590	88.10%	753	75.15%	856	51.60%	999
98.66%	591	87.77%	756	75.13%	856	51.29%	1001
98.57%	594	87.73%	757	75.12%	856	51.20%	1002
98.49%	595	87.62%	758	75.05%	857	50.27%	1007
98.34%	599	87.30%	761	75.03%	857	49.84%	1010
98.07%	605	86.77%	766	74.95%	857	49.73%	1011
97.35%	621	86.76%	766	74.79%	858	49.73%	1011
97.24%	624	86.64%	767	74.77%	859	48.68%	1017
97.10%	627	86.62%	767	74.31%	862	46.65%	1029
97.04%	628	86.53%	768	74.13%	863	46.45%	1031
96.75%	634	86.31%	770	74.02%	863	44.10%	1045
96.64%	636	86.30%	770	73.98%	864	43.83%	1047
96.40%	641	85.49%	778	73.72%	865	43.77%	1047
96.27%	644	85.43%	778	73.71%	866	43.13%	1051
96.17%	646	85.34%	779	73.67%	866	41.59%	1061
95.91%	651	85.27%	780	73.37%	868	41.11%	1064
95.89%	651	85.18%	780	73.31%	868	40.92%	1065
95.83%	652	85.06%	782	73.28%	868	39.76%	1073
95.53%	657	84.85%	783	72.77%	872	39.20%	1076
95.41%	659	84.82%	784	72.60%	873	39.19%	1076
95.38%	660	84.81%	784	72.58%	873	38.80%	1079
95.25%	662	84.77%	784	72.46%	874	38.02%	1084
94.86%	669	84.57%	786	72.02%	876	37.47%	1087
94.73%	671	84.17%	789	71.99%	876	37.17%	1089
94.66%	672	84.13%	790	71.76%	878	37.01%	1090
94.65%	672	84.12%	790	71.51%	880	36.75%	1092
94.52%	674	83.89%	791	71.39%	880	36.01%	1097
94.35%	677	83.63%	794	71.15%	882	34.88%	1104
94.03%	682	83.60%	794	70.96%	883	34.57%	1106
93.81%	685	83.60%	794	70.57%	885	34.08%	1109
93.59%	688	83.42%	795	70.48%	886	33.53%	1113
93.25%	693	83.22%	797	70.24%	887	32.91%	1117
93.22%	694	82.99%	799	70.19%	888	31.99%	1123
93.01%	697	82.98%	799	70.10%	888	31.95%	1123
92.89%	699	82.76%	801	70.08%	888	30.57%	1132
92.81%	700	82.70%	801	70.05%	889	29.70%	1137
92.61%	703	82.69%	801	69.92%	889	29.69%	1137
92.44%	705	82.68%	801	69.58%	891	29.57%	1138
92.41%	705	82.61%	802	69.33%	893	26.65%	1157
92.39%	706	82.49%	803	69.21%	893	26.54%	1158
92.35%	706	82.34%	804	68.72%	896	26.09%	1160
92.27%	707	82.25%	805	68.42%	898	25.82%	1162
92.10%	709	82.21%	805	68.38%	898	25.04%	1167
92.07%	710	82.06%	806	67.80%	902	17.27%	1220
91.90%	712	81.90%	807	67.51%	904	16.98%	1222
91.88%	712	81.87%	808	67.44%	904	14.65%	1238
91.85%	712	81.87%	808	66.44%	910	14.56%	1239
91.79%	713	81.48%	810	65.00%	918	14.26%	1241
91.76%	713	81.07%	814	64.32%	923	12.82%	1251
91.67%	715	80.67%	817	64.29%	923	12.35%	1255
91.39%	718	80.29%	819	64.20%	923	5.16%	1308

A.5. Sensitivity analysis

Here, the projected EU carbon price for 2030 is adjusted within a range of ±10%, and the resulting government price and market price curves are presented in Fig. A3. In the figure, the yellow and blue lines represent the government price curves corresponding to a 10% increase and a 10% decrease in the EU carbon price, respectively. The shaded gray area between them represents other values within the interval. It can be observed that adjustments to the government price lead to variations in the final results. However, all different values intersect with the market price curve, satisfying the model requirements and yielding the corresponding final carbon price.

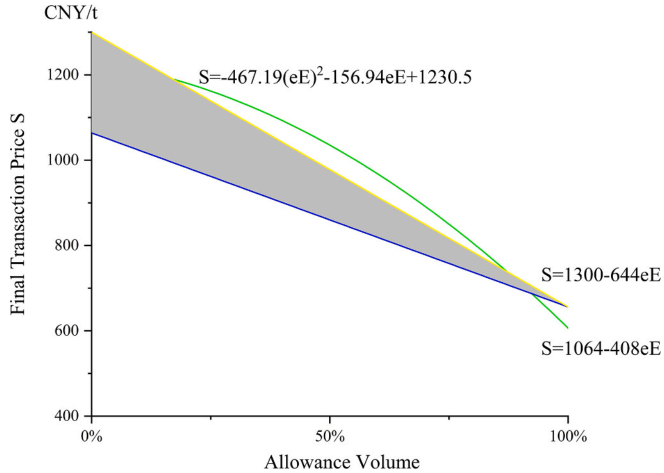

Fig. A3: The sensitivity analysis of government price.

Data availability

I have shared the link to my data.

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