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Article

Carbon futures contract design and theoretical pricing in China's National Carbon Market

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ABSTRACT

The hedging, intertemporal arbitrage, and price discovery functions of carbon futures can help alleviate the problems of insufficient liquidity, limited trading volume, and high price volatility in the spot trading of carbon allowances in China's National Carbon Market. This paper, considering China's institutional context, explores the design of carbon futures contracts for the National Carbon Market and investigates their pricing. First, it selects CEAs as the underlying asset for carbon futures, based on their homogeneity, significant price volatility, and considerable market potential. Second, drawing on the characteristics of China's market system and compliance requirements, it designs the contract specifications for CEAs futures, covering fundamental trading elements, delivery arrangements, and risk control mechanisms, to ensure both tradability and robust risk management. Finally, the paper develops a cost-of-carry pricing model, a no-arbitrage interval pricing model and a policy-adjusted model for CEAs futures based on no-arbitrage theory. The results show that the pricing outcomes of these models are closely aligned. This paper offers valuable insights for regulators and market participants on contract design and risk management in China's National Carbon Market.

KEYWORDS

China's National Carbon Market, risk management, carbon allowance futures, price discovery, carbon finance policy.

1 Introduction

With the intensification of global climate change, the low-carbon economy has become a dominant trend in global economic development[1–3]. As the world's largest emitter of greenhouse gases, China is under substantial pressure to reduce its carbon emissions. To address this challenge, China has set the ambitious goals of peaking carbon emissions before 2030 and achieving carbon neutrality before 2060. Since 2011, China has actively explored and piloted carbon market mechanisms, gradually establishing eight regional pilot emissions trading systems[4] and, on July 16, 2021, officially launched the national carbon emissions trading market[5]. These efforts are intended to use market-based instruments to promote corporate emission reductions, optimize the energy structure, and foster sustainable economic development[6–7].

Since the launch of the National Carbon Market, however, the spot market for carbon emission allowances has been constrained by a limited range of participants, resulting in relatively inactive trading, small transaction volumes, and limited emission-reduction effectiveness. Moreover, because the spot market is still in its initial phase, allowance prices have experienced frequent fluctuations, leading to uncertainty in compliance costs for regulated firms, without effective mechanisms for risk management.

Drawing on the experience of mature international carbon markets, such as the European Union Emissions Trading System (EU ETS), carbon futures can provide important functions (enhancing liquidity, improving price discovery, stabilizing price volatility, facilitating risk management, and enabling hedging) that can invigorate spot market and increase the incentives for regulated enterprises to reduce emissions[8–10]. As financial derivatives with carbon allowances as the underlying asset, carbon futures not only offer compliance entities effective tools to hedge against carbon price uncertainty and strengthen emission-reduction incentives but also enhance the vibrancy of the carbon market, improve the price formation mechanism, and contribute to China's influence in international carbon markets.

Against this backdrop, this study explores the design of carbon futures contracts for China's National Carbon Market as well as their pricing. First, the study identifies national carbon emission allowances (CEAs) as the underlying asset, based on their homogeneity, pronounced price volatility, and considerable market potential. Second, the contract specifications for CEAs futures are developed in line with China's institutional context and compliance requirements, encompassing trading elements (trading venue, contract size, tick size), delivery elements (contract months, delivery methods, delivery dates), and risk-control elements (price limits, margin requirements, and forced liquidation rules), thereby ensuring both tradability and robust risk management. Finally, based on no-arbitrage principles, the study constructs a cost-of-carry model, a no-arbitrage interval pricing model and a policy-adjusted model to estimate the theoretical price of CEAs futures. The results indicate that the pricing outcomes of these models are closely aligned, with the cost-of-carry model consistently yielding prices within the no-arbitrage interval, and the policy adjustment mainly induces a modest inward shift (upper bound down, lower bound up).

Despite the rapidly growing policy interest in introducing carbon derivatives in China, the existing literature provides

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limited guidance on a China-specific, implementable futures design and pricing framework for the national ETS. This paper fills this precise gap by offering an integrated "contract design + theoretical pricing" analysis tailored to CEAs. On the analytical side, we develop a coherent no-arbitrage pricing framework consisting of a cost-of-carry model, a no-arbitrage interval model, and a policy-adjusted model that formalizes how policy frictions can shift theoretical pricing bounds. On the practical and policy side, we translate institutional constraints into operational contract specifications (trading, delivery, and risk-control elements), thereby providing actionable benchmarks for exchanges and regulators when assessing market feasibility, risk management effectiveness, and the potential for improved price discovery and liquidity. Overall, the contribution is primarily policy-oriented and practice-relevant, supported by conceptual structuring of institutional features and analytical modeling that yields transparent pricing and design implications.

The remainder of this paper is structured as follows: Section 2 reviews the current state of China's National Carbon Market, identifying key challenges and underlying causes. Section 3 discusses the role of carbon futures in promoting the development of the spot market. Section 4 presents the design of carbon futures contracts. Section 5 analyzes the theoretical pricing of these contracts. Section 6 concludes the study.

2 Trading status of China's National Carbon Market

2.1 Current status of trading

The spot trading of carbon emission allowances in China's National Carbon Market currently exhibits the characteristics of a nascent market: it is primarily compliance-driven, suffers from insufficient liquidity, is dominated by block trades, operates on a limited scale, and is marked by significant price volatility.

(1) Compliance-driven trading as the dominant pattern

At present, the National Carbon Market displays "compliance-driven" feature, with trading activity concentrated in the months preceding the allowance surrender deadline, particularly in the second half of the year. This creates a pronounced "tidal phenomenon," while market activity during the non-compliance period remains extremely low or nearly stagnant. As shown in Figure 1, the market follows seasonal rhythm: trading volumes and values in the second half of the year, especially in the fourth quarter, are significantly higher than those in the first half. The trading peaks generally occur in the months leading up to the December 31st compliance deadline, whereas the first half of the year is characterized by weak activity, with some periods approaching complete stagnation.

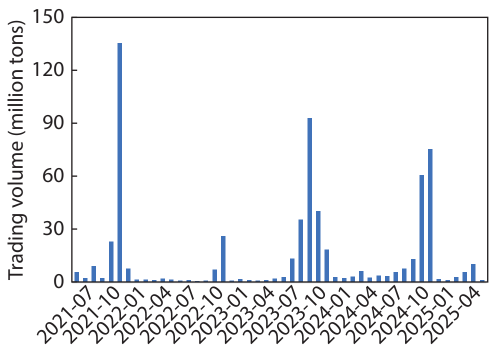

Fig. 1 Monthly trading volume of China's National Carbon Market.

(2) Insufficient liquidity

Turnover ratio is a key indicator for measuring market liquidity, as it directly reflects the frequency with which allowances are traded in the market[11]. In international comparisons, the annual turnover ratio is commonly used; it is calculated as the ratio of the cumulative annual trading volume to the total volume of tradable allowances in circulation. As illustrated in Figure 2, the annual turnover ratio of China's National Carbon Market has consistently remained below 5%, which is far lower than that observed in mature international carbon markets, such as the EU ETS. This indicates that the National Carbon Market suffers from liquidity shortages, with trading activity only temporarily activated under the pressure of compliance obligations.

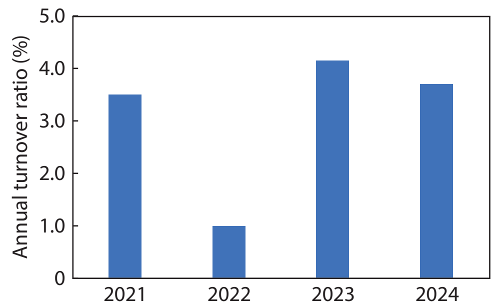

Fig. 2 Annual turnover rate of China's National Carbon Market.

(3) Imbalanced trading structure

As shown in Figure 3, during the full trading years from 2021 to 2024, block trades consistently accounted for more than 80% of total trading volume, while exchange-based continuous auction trades represented less than 20%. This excessive reliance on block trades has led to a structural imbalance that poses challenges to the market's price discovery function. Prices in block trades are usually negotiated privately between counterparties, resulting in relatively low transparency, and such trades do not generate a continuous and publicly observable price sequence. Consequently, the high-frequency and transparent market price signals are either severely missing or distorted. This undermines the effectiveness of carbon prices as a reliable signal for resource allocation.

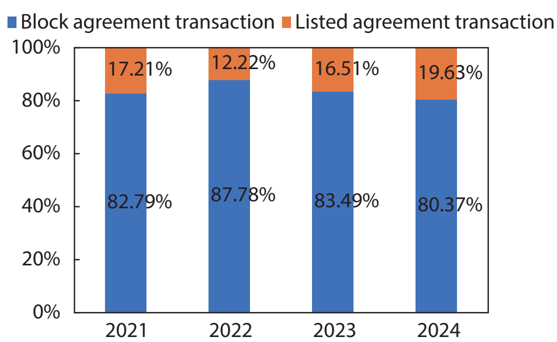

Fig. 3 Annual share of block and listed agreement transactions in China's National Carbon Market.

(4) Relatively limited market scale

Figure 4 illustrates the annual trading volumes and values of carbon emission allowances in China's National Carbon Market. In 2021, the trading volume was 179 million tons, while in 2022 it fell to only 51 million tons; in 2023, it rebounded to 212 million tons, and in 2024 it reached 184 million tons. In terms of trading value, the total was RMB 7.66 billion in 2021, RMB 2.81 billion in

2022, RMB 14.4 billion in 2023, and RMB 17.6 billion in 2024. Despite pronounced trading peaks during the compliance season, the annual total trading volume and value remain low compared with the scale of emissions covered by the market.

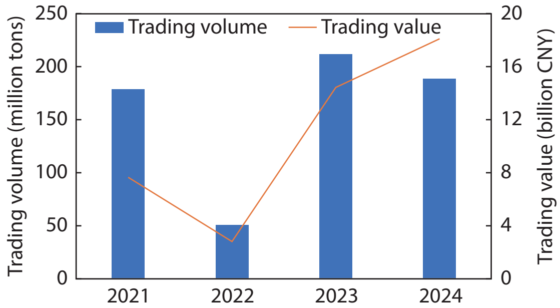

Fig. 4 Annual trading volume and trading value of China's National Carbon Market.

(5) Significant price volatility

Figure 5 presents the daily trading prices of carbon emission allowances in China's National Carbon Market. From 2021 to 2023, prices fluctuated within the range of RMB 50–60 yuan per ton, with occasional dips into the RMB 40s yuan. In the second half of 2024, prices rose markedly, repeatedly surpassing RMB 100 yuan per ton, though such levels were not sustained for long. By early 2025, prices had retreated to around RMB 70 yuan per ton, representing a decline of more than 30% from the previous peak. Over the entire period, prices oscillated between RMB 40 yuan and RMB 110 yuan per ton, with frequent highs and lows, indicating a high level of market volatility.

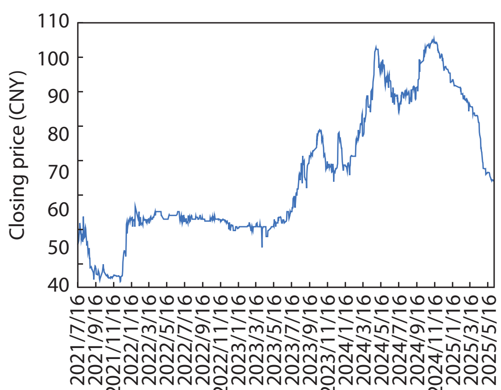

Fig. 5 Closing price of China's National Carbon Market.

2.2 Underlying causes

The lack of activity in the spot trading of carbon allowances in the National Carbon Market is the result of multiple interrelated factors, which can be summarized as follows:

First, insufficient supply-side willingness suppresses market activity. Compliance entities generally display strong reluctance to sell allowances, driven by motives beyond short-term profit considerations. On the one hand, under the "dual carbon" goals and expectations of tightening allowance allocation, firms increasingly treat allowances as strategic assets with significant appreciation potential, fostering a tendency toward long-term holding. On the other hand, concerns about future policy tightening (e.g., declining benchmarks and reduced free allocation) prompt companies to hoard surplus allowances to hedge against the risk of expensive future purchases. Moreover, the mechanism of free allocation fosters a "zero-cost mentality," leading firms to perceive allowance sales as asset loss rather than optimal resource reallocation.

Second, demand-side homogeneity and weak incentives result in fragile buyer power. The market is severely imbalanced, as buyers are almost exclusively compliance entities with shortfalls, while banks, insurers, and other institutional investors remain largely absent. Demand exhibits both "passive" and "seasonal" characteristics concentrated in rigid procurement before compliance deadlines, with little day-to-day trading demand. At the same time, price regulation in the electricity sector obstructs the pass-through of carbon costs, weakening incentives for firms to optimize cost structures via market transactions. Instead, they rely more on internal reallocation or policy support[12–13].

Third, market design and institutional factors also constrain allowance trading[14]. At the institutional level, loose allocation in the early stages created an overall surplus, reducing the urgency of trading. Uncertainty regarding the trajectory of cap reduction and allocation rules directly reinforces firms' reluctance to sell. In terms of infrastructure, the absence of carbon financial derivatives (e.g., futures, options, forwards) limits the functions of price discovery and risk management. In addition, an underdeveloped MRV (monitoring, reporting, and verification) system undermines firms' ability to accurately assess their own allowance positions.

Fourth, distorted price signals hinder firms from managing carbon price expectations effectively. Insufficient liquidity prevents allowance prices from reflecting the true marginal cost of abatement, leading to a failure in the price formation mechanism. Furthermore, early policy interventions, such as allowance agreement transfers and supply adjustments, have instilled a "price floor" expectation among market participants. While this reduces firms' willingness to sell in low-price ranges, it fails to stimulate corresponding buyer demand[15].

In sum, the subdued activity in China's National Carbon Market reflects a systemic and structural issue. This includes strong supply-side hoarding motives (rooted in expectations of scarcity, future price increases, and policy uncertainty), a narrow and passive demand structure (driven primarily by compliance gaps and lacking institutional investor participation), deficiencies in market design (loose allocation, unstable expectations, and the absence of carbon financial instruments), and distorted price signals that fail to guide rational market behavior.

3 Functions of carbon futures and related derivatives

Considering the current trading situation and its underlying causes in China's national carbon allowance spot market, carbon futures and other financial derivatives can, by providing specialized risk management tools, help mitigate some of these issues and thereby effectively complement and promote the development of the National Carbon Market.

First, carbon futures and related derivatives offer tools for hedging carbon price risk. Futures, options, and forwards enable compliance entities to lock in future carbon prices and manage long-term price volatility[16]. By purchasing futures contracts or call options, firms can hedge against the risk of costly allowance purchases in the event of future shortfalls. For instance, in the EU carbon market, most compliance entities rely on futures contracts to manage exposure to carbon asset risks, which significantly enhances their willingness to sell in the spot market. This enhanced risk management capacity alleviates the precautionary hoarding motive stemming from concerns over tighter allowance allocation, making surplus allowances more likely to enter secondary market circulation.

Second, carbon futures and related derivatives create opportunities for intertemporal arbitrage. Derivatives trading establishes a market-based pricing benchmark for carbon assets, allowing firms to better assess the opportunity cost of holding allowances. The continuous price curve generated by the futures market highlights the implicit cost of reserve allowances and incentivizes firms to adopt proactive trading strategies based on implied forward prices. The spread between futures and spot prices (the basis) gives rise to arbitrage strategies[17] that induce firms to actively adjust their allowance inventories. When futures prices exceed spot prices (a contango structure), firms tend to "sell futures + hold spot" for arbitrage; conversely, when spot prices exceed futures prices (a backwardation structure), firms are encouraged to accelerate spot sales. Such arbitrage mechanisms enhance allowance turnover, unlock liquidity in existing holdings, and counteract the "zero-cost mentality" and passive "hold-to-maturity" strategies fostered by free allocation.

Third, carbon futures and related derivatives strengthen the price discovery function. On one hand, futures prices immediately incorporate market expectations regarding future policies (e.g., tighter allocation, expanded sectoral coverage), technological progress (e.g., declining renewable energy costs), and macroeconomic conditions (e.g., GDP growth, energy demand), thereby guiding spot prices and dampening short-term volatility[18–19]. On the other hand, the futures term structure produces a continuous carbon price curve from the near term to the long term, rendering carbon cost information intertemporally visible and enabling firms to extend abatement and investment planning horizons from one year to five to ten years. Moreover, the shape of the term structure conveys signals about allowance scarcity: a pronounced contango typically indicates a loose allocation or higher holding costs, while a marked backwardation reflects tighter supply and increased convenience yield. Such signals guide compliance entities in dynamically adjusting procurement, compliance, and arbitrage strategies, while also providing observable market feedback to inform refinements in allocation rules.

Fourth, carbon futures and related derivatives attract a more diversified set of participants and generate new forms of trading demand. On the one hand, the standardized nature of futures contracts renders carbon assets investable, thereby attracting participation from financial institutions. The price differentials between futures and spot markets or among contracts of different maturities create opportunities for statistical arbitrage, drawing in institutional investors and further boosting trading activity. On the other hand, incorporating carbon futures into investment portfolios allows institutional investors to leverage the correlation characteristics of carbon assets with equities and bonds to meet their asset allocation objectives[20–21].

4 Design of carbon futures contracts

Carbon futures refer to standardized contracts, formulated by futures exchanges, that stipulate the delivery of a specified quantity of carbon allowances or carbon credits at a predetermined time and place in the future. As a type of futures product, carbon futures must adopt standardized contracts, under which the trading time, characteristics of the underlying commodity (carbon assets), and trading methods are pre-specified. Such contracts are typically listed and traded on exchanges.

4.1 Selection of the underlying assets

The choice of the underlying assets is central to the design of carbon futures, as it directly affects the market's acceptance of the contract, the effectiveness of risk hedging, and the robustness of price discovery. Given the developmental stage and policy framework of China's National Carbon Market, national carbon emission allowances (CEAs) are currently the most suitable underlying asset for carbon futures contracts.

First, the standardized and homogeneous nature of carbon emission allowances. CEAs are uniformly issued by the Ministry of Ecology and Environment, with each unit of allowance strictly corresponding to the right to emit one metric ton of CO_2-equivalent. In the National Carbon Market, CEAs possess identical value attributes and compliance effectiveness. This top-level institutional design ensures the fungibility of CEAs, completely eliminating heterogeneity risks that may arise from regional or sectoral differences, thereby meeting the rigid requirement of futures contracts for asset uniformity.

Second, the significant price volatility of carbon emission allowances stimulates hedging and speculative demand. On the one hand, pronounced price fluctuations amplify uncertainty in compliance costs and cash flows, generating persistent hedging needs and positioning futures as an effective instrument for transferring risk from compliance entities to risk-bearing investors. On the other hand, sufficient and tradable volatility provides risk premiums and strategic opportunities for market makers and speculative capital, attracting liquidity provision, narrowing bid-ask spreads, and establishing a "hedging pressure-risk premium" mechanism that reinforces the sustainability of the futures contract ecosystem.

Finally, the market potential of carbon emission allowances as an underlying is substantial. On March 26, 2025, the Ministry of Ecology and Environment released the Work Plan for Expanding the Coverage of the National Carbon Emissions Trading Market to the Steel, Cement, and Aluminum Sectors, marking the official implementation of the first expansion of sectoral coverage in China's national carbon trading system. The National Carbon Market currently covers around 2,200 key emitters in the power generation sector, with annual coverage of more than 5 billion tons of CO_2 emissions, approximately 40% of China's total emissions. The steel, cement, and aluminum smelting industries are major emitters, with annual emissions of about 3 billion tons of CO_2-equivalent, accounting for over 20% of national emissions. Following this expansion, the National Carbon Market is expected to add approximately 1,500 new key emitters, increasing its coverage to over 60% of China's total CO_2 emissions and extending the scope of covered greenhouse gases from carbon dioxide to include perfluorocarbons (CF_4) and hexafluoroethane (C_2F_6). The sheer volume of allowances under management thus provides a solid foundation for the establishment of a carbon futures market.

4.2 Design of contract elements

4.2.1 Basic elements

(1) Contract code

The contract code for national carbon emission allowance (CEA) futures is designed using a three-part structure: underlying code + contract type + maturity month, in order to balance international practice with domestic market characteristics. The underlying asset adopts the existing national carbon allowance code “CEA” as the prefix, with the futures type denoted by “F,” and the maturity month represented in either four or six digits. For example, the code for the December 2025 contract would be CEAF202512. This structure ensures compatibility with EU Allowance (EUA) futures (e.g., EUAF202512), while maintaining the concise and straightforward style typical of Chinese commodity futures.

(2) Trading unit

In designing the trading unit for national CEA futures contracts, multiple factors must be considered, including the fundamentals of the spot market, the characteristics of market participants, the efficiency of price discovery, and the requirements of international alignment. The trading unit is set at 1,000 metric tons of CO_2-equivalent per lot. This design is based on the following considerations: first, while spot trading in the National Carbon Market uses “tons” as the basic unit, the leverage characteristic of futures markets and the predominance of institutional investors suggest that 1,000 tons per lot is more appropriate, effectively reducing transaction friction associated with small-lot trades (e.g., lowering the proportional burden of transaction fees). Second, the major international carbon futures exchanges all adopt 1,000 tons of CO_2-equivalent per lot, including the Intercontinental Exchange (ICE), European Energy Exchange (EEX), Chicago Climate Futures Exchange (CCFE), New York Mercantile Exchange (NYMEX), and NASDAQ-OMX. This alignment ensures consistency with mainstream global markets and provides space for future cross-border trading.

(3) Quotation unit and minimum price fluctuation

In designing the quotation unit and minimum tick size for national CEA futures, it is essential to balance market liquidity, price discovery efficiency, and the practical needs of participants. Based on international experience and the specific characteristics of China’s market, the quotation unit is set as RMB per ton, and the minimum tick size as 0.1 RMB/ton. This design is grounded in three key considerations: first, a minimum tick of 0.1 RMB/ton is broader than the 0.01 EUR/ton (approximately 0.07 RMB/ton) used in EUA futures, which ensures price continuity while avoiding excessive fragmentation in quotations caused by overly fine increments. Second, for compliance entities with annual emissions on the order of 100,000 tons, a fluctuation of 0.1 RMB/ton implies that the value of a single contract (1,000 tons/lot) changes by 100 RMB, which adequately meets firms’ hedging needs for marginal abatement costs while avoiding price jumps so large that precise hedging becomes impractical. Finally, the scheme has institutional scalability. At the initial listing stage, a conservative setting of 0.1 RMB/ton can be adopted; once the market matures, a phased adjustment mechanism (modeled after ICE) may be introduced to dynamically optimize the minimum tick size based on average daily trading volume (e.g., reducing it to 0.05 RMB/ton when turnover exceeds 500,000 lots per day).

4.2.2 Delivery elements

(1) Contract months

In designing the contract months for national carbon emission allowance (CEA) futures, adopting the quarterly cycle of March, June, September, and December is both consistent with international practice and aligned with the characteristics of China’s National Carbon Market. Mature markets such as EUA futures in the EU also use quarterly contracts as the benchmark (with December contracts serving as the annual benchmark). Using the same quarterly cycle facilitates future cross-border arbitrage and price anchoring. It is recommended to designate the December contract as the annual benchmark contract, as in the EU carbon futures market where December contracts consistently account for more than 60% of trading volume.

(2) Last trading day and delivery date

When designing the last trading day and delivery date of national CEA futures contracts, three principles should be followed: “avoid policy window periods, align with spot delivery processes, and allow time for risk resolution.” It is recommended to adopt the mechanism whereby the last trading day is set as the fifth trading day prior to the end of the contract month, and the delivery date is set as the third business day after the last trading day. This design is based on the following considerations:

First, the timing arrangement accounts for the policy cycle characteristics of China’s National Carbon Market. By setting the last trading day as the fifth trading day before the end of the contract month, the design avoids overlapping with year-end corporate financial settlement peaks and the spot market compliance deadline, thereby preventing market volatility from coinciding with critical policy dates. Ending trading five days in advance also provides ample time for rollovers, reducing the risk of liquidity shortages and the “maturity effect.”

Second, the delivery process ensures seamless integration of futures and spot markets. The arrangement of delivery on the third business day after the last trading day incorporates three safeguards: 1) on the first business day, funds settlement and position reconciliation are completed through multilateral netting conducted by the clearinghouse; 2) on the second business day, allowance transfers are executed through the China Emissions Exchange Registry (C-Carbon Registry) under a Delivery versus Payment (DVP) mechanism, ensuring simultaneous transfer of funds and allowances; 3) the third business day serves as a contingency period to handle defaults or other exceptional circumstances. This arrangement reflects both the delivery conventions of Chinese commodity futures and the registration and settlement requirements specific to carbon allowances.

Finally, this scheme establishes a robust risk management buffer. The three-day interval between the last trading day and the delivery date allows the exchange to conduct key operations: 1) adjust the size of the default disposal reserve (set at 20% of the value of open contracts); 2) initiate large-position reporting requirements (penetrating supervision of clients holding more than 50,000 lots). A special provision is included: if the last trading day coincides with a national holiday, it is moved to the preceding trading day, while the delivery date must strictly adhere to the “trade date + 3 business day” interval, thereby effectively mitigating holiday-related liquidity risks.

(3) Delivery method

In the design of national carbon futures contracts, delivery may be conducted via cash settlement or physical delivery. This paper proposes physical delivery, whereby upon contract maturity the ownership of carbon allowances is actually transferred between buyers and sellers through the C-Carbon Registry, rather than settled in cash. The choice of physical delivery is based on three main reasons: first, physical delivery effectively links futures with spot markets, ensuring price convergence and avoiding the potential price divergence that cash settlement may cause; second, as carbon allowances are policy-created instruments for emission reduction, physical delivery better serves the actual needs of compliance entities, enhancing the hedging function of the futures market; third, given that China's National Carbon Market is still in its early stages, physical delivery aligns with regulatory requirements, supports stable market operation and participant cultivation, and is consistent with the tradition of Chinese commodity futures, thereby facilitating acceptance and operational feasibility.

4.2.3 Risk control elements

(1) Daily price limits

The daily price limit of a futures contract is a key mechanism for controlling market risk. The daily price limit refers to the maximum permissible price fluctuation range for a futures contract within a single trading day, as stipulated by the futures exchange[22]. It is designed to curb excessive speculation and volatility. When price changes exceed the set threshold during a trading session, trading is suspended. This threshold, commonly expressed as a fixed value or percentage, is referred to as the daily price limit. In China's commodity futures markets, a percentage-based system is generally adopted. The purpose of this mechanism is to mitigate risks arising from excessive price fluctuations, safeguard investors' returns, and maintain stable market operations.

Internationally, almost all jurisdictions offering carbon futures have no price limit system in place. The only exception is India, where a tiered daily price limit is applied at 4%, 5%, and 9%. In the United States and the European Union, where carbon financial markets are relatively mature, no daily price limits are imposed. However, given that China's carbon financial market remains underdeveloped and investors are not yet fully mature in their trading behavior, it is advisable to establish a daily price limit system during the initial operational stage of the carbon market. As the market improves, adjustments can be made accordingly. In China's commodity futures markets, daily price limits typically range between 5% and 10%.

The design of daily price limits for carbon futures should be tailored to China's specific conditions, considering both the frequency and amplitude of price fluctuations in the spot carbon market. The limits must be broad enough to accommodate normal market movements, yet sufficiently restrictive to suppress potential irrational behavior. The scope of the daily price limit should correspond to the degree of volatility in the underlying asset: a wider limit for higher spot price volatility, and a narrower one for more stable price movements.

Currently, the daily price fluctuation limit for listed agreement-based trading of national carbon emission allowances (CEAs) is set at 10%. For this study, we selected the daily closing prices of CEAs in the National Carbon Market from July 16, 2021, to June 4, 2025, yielding a sample of 929 observations. The calculation formula for daily price volatility is: Daily price volatility = (closing price on day t − closing price on day (t−1)) / closing price on day (t−1) × 100%.

Our calculations show that the maximum daily volatility of CEA spot trading was +9.843%, the minimum was −9.786%, with an average of 0.046% and a standard deviation of 1.756. As presented in Table 1, out of 928 valid results, 97.52% of daily fluctuations fell to within 5%. Therefore, a daily price limit of ±5% would adequately cover most price movements. Considering that the National Carbon Market remains in its early stage of development, it would be inappropriate to adopt overly large limits for CEA futures. Based on the above analysis, this study proposes setting the daily price limit for China's CEA futures at 5%, which would provide effective risk control.

Table 1 Absolute daily price fluctuations in China's National Carbon Market.

Range	Percentage	Cumulative percentage
[0, 1%]	68.32%	68.32%
(1%, 2%]	14.87%	83.19%
(2%, 3%]	7.97%	91.16%
(3%, 4%]	4.53%	95.69%
(4%, 5%]	1.83%	97.52%
(5%, 6%]	1.08%	98.60%
(6%, 7%]	0.43%	99.03%
(7%, 8%]	0.43%	99.46%
(8%, 10%]	0.54%	100.00%

(2) Minimum margin requirement

The margin system, as a core risk management mechanism of the futures market, is directly related to market stability and operational efficiency[23]. Functionally, the minimum margin requirement carries multiple regulatory values: it constrains excessive speculation, reduces default risk by setting a financial threshold, and dampens abnormal volatility arising from leveraged trading. Exchanges typically adjust the minimum margin dynamically on the basis of liquidity, volatility, and other indicators to maintain the effectiveness of risk control. In setting the requirement, a comprehensive evaluation must be made of investors' risk tolerance, market conditions, and the balance between risk and return.

Internationally, carbon futures margin systems generally follow two models: a fixed-amount system, as practiced in Europe and the United States, and a proportional system, as adopted in India. The New York Mercantile Exchange, for instance, applies a differentiated approach, requiring an initial margin of €715 for speculators and a maintenance margin of €650 for hedgers. By contrast, the Indian market uses a fixed-ratio model, requiring an initial margin equal to 6% of the contract value. Referring to China's commodity futures convention of 6%–15% margin ratios, and considering the specific characteristics of the carbon futures market in its early stage of development, setting the minimum margin requirement at 10% of the contract value is deemed reasonable. This level not only preserves the exchange's operational flexibility to adjust in either direction as market conditions evolve, but also provides effective control over potential risks during the market's formative phase, achieving a balance between liquidity and stability.

(3) Position limits and large trader reporting

As critical risk control mechanisms for carbon allowance futures contracts, the position limit and large trader reporting systems play a vital role in preventing market manipulation and maintaining orderly trading. The position limit system caps the maximum number of contracts that a member or client may hold in a given futures contract, effectively constraining the market influence of any single participant. Meanwhile, the large trader reporting system requires participants whose positions exceed a predefined threshold to disclose relevant information, enabling the exchange to monitor potential risks in a timely manner. The coordinated implementation of these two mechanisms not only deters attempts to manipulate the market through concentrated positions but also provides regulators with an early-warning tool to neutralize systemic risks at an early stage.

(4) Mark-to-market settlement system

As a core clearing mechanism of the futures market, the mark-to-market settlement system plays a foundational role in the design of carbon allowance futures contracts. Under this system, the clearinghouse revalues all open positions at the end of each trading day based on the daily settlement price, calculates the profit and loss of each member or client, and processes real-time transfers of margin, fees, and other related funds. Operating under a central counterparty clearing model, the clearinghouse acts as the common counterparty to all trades, substantially reducing credit risk exposure through multilateral netting and assuming the guarantee obligation in cases of default, thereby ensuring the proper fulfillment of contracts.

(5) Forced liquidation mechanism

The forced liquidation mechanism, as a key component of the risk control framework for the carbon allowance futures market, is an essential safeguard of stable market operations. This mechanism authorizes the exchange to take mandatory liquidation measures under specific risk circumstances, primarily when a member or client fails to meet margin requirements, violates position limits, or engages in serious illegal or non-compliant behavior. From a design perspective, forced liquidation is not merely a punitive measure against rule violations; it also serves as a crucial safeguard to ensure the effective functioning of core systems such as mark-to-market settlement, position limits, and margin requirements.

In summary, the design of China's National Carbon Market allowance futures contracts is as Table 2.

5 Theoretical pricing of carbon futures contracts

5.1 Theoretical foundations and model selection

The pricing mechanism of carbon futures is a central issue in carbon finance research and constitutes a fundamental basis for building an effective carbon market[24–25]. Following the detailed design of China's carbon futures contracts, this section systematically examines the theoretical foundations and methods of carbon futures pricing. A sound and rigorous futures pricing mechanism not only directly influences the effectiveness of product design but also affects the trading incentives of market participants and the stable development of the entire carbon market. From a practical perspective, an accurate pricing mechanism can provide reliable price signals to participants, thereby promoting the efficient allocation of carbon resources[26–27].

Within the theory of financial derivatives pricing, the no-arbitrage principle serves as the most fundamental and core analytical framework. The essence of this approach lies in the notion that when the market price of a derivative deviates significantly from its theoretical value beyond the extent explainable by transaction costs and other frictions, rational market participants will construct arbitrage portfolios to capture risk-free profits. Specifically, investors buy the undervalued asset while simultaneously selling the overvalued asset. Such arbitrage activity triggers an endogenous market adjustment mechanism: the price of the undervalued asset rises as demand increases, while the price of the overvalued asset falls as supply increases. This dynamic process continues until market prices converge toward the theoretical equilibrium level, at which point arbitrage opportunities are fully eliminated and the market reaches a no-arbitrage equilibrium. The resulting equilibrium price represents the fair value of the derivative under the no-arbitrage condition.

From a theoretical development perspective, carbon futures pricing models based on the no-arbitrage principle can be divided into three major categories:

(1) Pricing models under complete market conditions. The most classic model in this category is the cost-of-carry model. Built on the strict assumption of a complete market, this model abstracts from real-world frictions such as transaction costs, lending–borrowing spreads, and short-selling constraints, expressing the carbon futures price simply as the sum of the spot price and the net cost of carry. When this relationship holds, no arbitrage opportunities exist in the market.

(2) Pricing models under relaxed complete market assumptions. These models more closely approximate real market environments and take three main forms. The no-arbitrage interval pricing model extends the traditional cost-of-carry model by incorporating real-world factors such as lending–borrowing spreads, transaction costs, and margin requirements, yielding a theoretical price expressed as a range rather than a single value. The continuous-time pricing model abandons the assumption of a fixed interest rate and instead treats interest rates as a stochastic process, thereby better capturing the volatility of interest rates observed in reality. However, given that China's interest rate liberalization reform is still underway, the applicability of this model remains relatively limited in the domestic context. The general equilibrium pricing model considers the joint stochastic nature of carbon spot prices and interest rates, establishing a more comprehensive pricing framework. Yet, this model requires

Table 2 Carbon emission allowance futures contract.

Trading code	Underlying code + contract type + maturity month (e.g., CEAF202512)
Trading unit	1,000 tons per lot
Quotation unit	RMB per ton
Minimum price Fluctuation	0.05 RMB/ton
Daily price limit	Previous trading day's settlement price ±5%
Minimum margin requirement	10% of contract value
Delivery months	Quarterly delivery: March, June, September, December
Last trading day	Fifth trading day prior to the end of the contract month
Final delivery day	Third business day after the last trading day
Delivery method	Physical delivery (allocation of CEAs via the National Carbon Emission Registry System)

substantial historical trading data for parameter estimation, an obstacle in the early stages of China's National Carbon Market, where such data are insufficient.

(3) Pricing models under incomplete market conditions. These models introduce the concept of market incompleteness to better capture frictions and constraints present in real-world markets. However, similar to the general equilibrium approach, they require extensive historical futures trading data for parameter estimation, which poses significant challenges in China's nascent carbon market.

In view of the feasibility of carbon futures pricing, this study selects the cost-of-carry model and the no-arbitrage interval pricing model as the primary analytical tools, with the aim of providing comprehensive and reliable pricing benchmarks for China's carbon emission allowance futures.

5.2 Carbon futures pricing models

5.2.1 Cost-of-carry model

The cost-of-carry theory is a classical and traditional analytical framework for examining the pricing of commodity futures[28]. The theory was first proposed by Keynes, who argued: "The phenomenon whereby futures contract prices are generally higher than spot prices (i.e., a positive spread) can be explained by this theory. However, when the market experiences an inverted structure, for example, when spot prices exceed futures prices, or when near-maturity contracts are priced higher than longer-maturity contracts, the explanatory power of the cost-of-carry theory becomes relatively limited."

The core proposition of this theory is that the theoretical price of a commodity futures contract consists of two components: (1) the costs incurred from holding the underlying spot commodity until the contract's maturity, and (2) the spot price formed in the market. Specifically, the cost of carry comprises several elements, including storage costs, transportation costs, insurance expenses, and interest costs associated with capital tied up in holding the commodity. Under market equilibrium, the cost of carry is primarily reflected in two aspects: the difference between futures and spot prices (the basis) and the price differentials among futures contracts with different maturities (calendar spreads).

For the cost-of-carry pricing model of carbon emission allowance futures, under the assumption of a complete market (i.e., ignoring frictions such as direct transaction costs in the carbon market, lending–borrowing rate differentials, and short-selling constraints in the spot market), the theoretical futures price can be expressed as the spot price plus the net cost of carry required to hold the spot until maturity. The fundamental pricing model can thus be stated as: the carbon futures price equals the spot price of carbon allowances plus the net cost borne by the investor for holding the spot until the contract's maturity.

Since holding spot carbon emission allowances does not involve physical storage or transportation costs (these costs are effectively zero), the cost of carry is primarily embodied in the cost of capital, that is, the interest paid when purchasing the spot through borrowing, or the opportunity cost incurred when using one's own capital to purchase the spot. This can be represented by Eq. (1):

$$F_{t,T} = S_t\,(1+u) \tag{1}$$

In this model, $F_{t,T}$ denotes the price at time t of a carbon allowance futures contract maturing at T. S_t represents the spot price of carbon allowances at time t. u is the proportion of the holding cost relative to the spot price S_t。

This model reveals the no-arbitrage equilibrium relationship between futures and spot prices: if an investor chooses to purchase the spot and hold it until futures maturity for physical delivery, then, to prevent arbitrage, the futures price should not exceed the sum of the spot price and the holding cost, that is, $F_{t,T} \leqslant S_t\,(1+u)$. Conversely, if the spot price is higher than the futures price, in theory investors could arbitrage by short selling the spot and buying the futures contract. Therefore, to eliminate arbitrage opportunities, the futures price should not fall below the spot price plus the holding cost, that is, $F_{t,T} \geqslant S_t\,(1+u)$. Equation (1) simultaneously satisfies both inequalities, thereby ensuring the validity of the no-arbitrage condition.

Given that the underlying asset of carbon futures (carbon emission allowances) possesses quasi-financial asset characteristics, the cost of carry is dominated by capital costs. Assuming the investor's financing cost equals the risk-free rate r, the discrete cost-of-carry model can be expressed as

$$F_{t,T} = S_t\,(1+r) \tag{2}$$

However, in practical pricing analysis, the applicability of the discrete model is limited due to the involvement of continuous compounding. It is therefore necessary to extend it to a continuous cost-of-carry pricing model:

$$F_{t,T} = S_t \mathrm{e}^{r(T-t)} \tag{3}$$

Regardless of whether the discrete or continuous cost-of-carry pricing model is applied, both are built upon the strict assumption of a complete market. Their limitations are mainly reflected in the following aspects: First, the model does not adequately account for market frictions such as direct transaction costs in the carbon allowance market, asymmetries in borrowing and lending rates, and the practical constraints on short selling in the spot market. Second, when the market exhibits an inverted structure in which futures prices fall below spot prices, the model struggles to reasonably explain the mechanism underlying negative carrying costs. Third, the model fails to incorporate the mark-to-market rule and margin requirements of futures trading, both of which introduce additional capital costs that directly affect the actual cost of carry. Fourth, the validity of the model relies on the assumption of market efficiency, namely that arbitrage forces can quickly eliminate price differentials and restore dynamic equilibrium. In real markets, however, where policy restrictions or insufficient liquidity may result in inefficiency or impede arbitrage activity, this mechanism may fail. In sum, while the cost-of-carry pricing model offers a theoretical approach to deriving futures prices based on the equilibrium relationship between spot and futures markets under strict assumptions, its application in complex real-world market environments requires cautious evaluation.

5.2.2 No-arbitrage interval pricing model

Given the numerous limitations of the cost-of-carry pricing model under strict assumptions, it is necessary to explicitly account for real-world factors such as direct transaction costs in the carbon allowance futures market, margin requirements for futures trading, and the spread between lending and deposit rates. By appropriately relaxing the assumptions of the cost-of-carry model, a no-arbitrage interval pricing model can be constructed that is more suitable for the study of carbon allowance futures pricing.

(1) Upper bound of the no-arbitrage pricing interval

At time t, a trader sells a carbon allowance futures contract at price $F_{t,T}$ and simultaneously purchases the underlying spot asset at price S_t in the spot market. At time t, the investor's required funds include the futures trading fee $\mu F_{t,T}$ and the margin requirement $\eta F_{t,T}$, as well as the cost of purchasing carbon allowances in the spot market, namely S_t plus direct transaction costs θS_t. These funds can be financed at the risk-free lending rate r_a. Here, μ, η and θ denote the trading fee rate of carbon allowance futures, the margin ratio, and the spot market transaction fee rate, respectively.

At the futures contract maturity date T, the trader completes settlement through delivery and sells the carbon allowances in the spot market to obtain arbitrage profits. The relevant cash flows include: the net proceeds from futures settlement $F_{t,T}$–S_t (which may be negative), the refund of margin $\eta F_{t,T}$, the proceeds from selling the allowances in the spot market $(1–\theta)S_t$, and the interest expenses $[(\mu+\eta)F_{i,T}+(1+\theta)S_t]\mathrm{e}^{r_a(T-t)}$. The cash flow process is shown in Table 3.

Table 3 Cash flows of the forward arbitrage strategy in CEAs futures.

Arbitrage strategy	Cash flow at time t	Cash flow at maturity T
Buy CEAs spot	$-(1+\theta)S_t$	$(1-\theta)S_t$
Sell CEAs futures	$-(\mu+\eta)F_{i,T}$	$F_{i,T}-S_t+\eta F_{i,T}$
Borrow funds	$(\mu+\eta)F_{i,T}+(1+\theta)S_t$	$-[(\mu+\eta)F_{i,T}+(1+\theta)S_t]\mathrm{e}^{r_a(T-t)}$
No-arbitrage equilibrium condition	$=0$	$\leqslant 0$

Under this arbitrage strategy, the cash flow at time t is zero. If the cash flow at maturity T is greater than zero, then a risk-free arbitrage profit can be obtained, namely: $(1+\eta)F_{i,T}-\theta S_t-[(\mu+\eta)F_{i,T}+(1+\theta)S_t]\mathrm{e}^{r_a(T-t)}>0$. Accordingly, the upper bound of the no-arbitrage pricing interval for carbon allowance futures, $F_{t,T}^{\text{upper}}$, is

$$F_{t,T}\leqslant F_{t,T}^{\text{upper}}=\frac{\theta S_t+(1+\theta)S_t\mathrm{e}^{r_a(T-t)}}{1+\eta-(\mu+\eta)\mathrm{e}^{r_a(T-t)}} \tag{4}$$

(2) **Lower bound of the no-arbitrage pricing interval**

If the carbon allowance futures price is significantly undervalued, investors may adopt a reverse arbitrage strategy by purchasing carbon allowance futures contracts while selling spot allowances. The specific strategy is as follows:

At time t, the trader buys a carbon allowance futures contract at price $F_{t,T}$ and simultaneously sells the spot asset in the market at price S_t. At time t, the trader receives funds from selling spot allowances S_t, and pays the spot transaction cost θS_t. At the same time, the trader must pay the futures trading fee $\mu F_{t,T}$ and the margin requirement $\eta F_{t,T}$. The net cash flow at time t can thus be expressed as $(1-\theta)S_t-(\mu+\eta)F_{i,T}$, which is deposited at the risk-free rate r_b.

At the futures contract maturity date T, the trader completes delivery and repurchases carbon allowances in the spot market to realize arbitrage gains. The relevant cash flows include: the futures settlement payment $F_{t,T}$–S_t (a negative value indicates profit), the refund of the futures margin $\eta F_{t,T}$, the payment for repurchasing spot allowances $(1+\theta)S_t$, and the accrued deposit interest $[(1-\theta)S_t-(\mu+\eta)F_{i,T}]\mathrm{e}^{r_b(T-t)}$. The cash flow process is shown in Table 4.

Table 4 Cash flows of the reverse arbitrage strategy in CEAs futures.

Arbitrage strategy	Cash flow at time t	Cash flow at maturity T
Sell CEAs spot	$(1-\theta)S_t$	$-(1+\theta)S_t$
Buy CEAs futures	$-(\mu+\eta)F_{i,T}$	$-(F_{i,T}-S_t)+\eta F_{i,T}$
Deposit funds	$-[(1-\theta)S_t-(\mu+\eta)F_{i,T}]$	$[(1-\theta)S_t-(\mu+\eta)F_{i,T}]\mathrm{e}^{r_b(T-t)}$
No-arbitrage equilibrium condition	$=0$	$\leqslant 0$

Under this arbitrage strategy, the cash flow at time t is zero. If the cash flow at maturity T is greater than zero, then a risk-free arbitrage profit can be obtained, namely: $(\eta-1)F_{i,T}-\theta S_t+[(1-\theta)S_t-(\mu+\eta)F_{i,T}]\mathrm{e}^{r_b(T-t)}>0$. Accordingly, the lower bound of the no-arbitrage pricing interval for carbon allowance futures, $F_{t,T}^{\text{floor}}$, is

$$F_{t,T}\geqslant F_{t,T}^{\text{floor}}=\frac{(1-\theta)S_t\mathrm{e}^{r_b(T-t)}-\theta S_t}{1+\eta-(\mu+\eta)\mathrm{e}^{r_b(T-t)}} \tag{5}$$

In summary, the no-arbitrage pricing interval for carbon allowance futures is

$$\left[\frac{(1-\theta)S_t\mathrm{e}^{r_b(T-t)}-\theta S_t}{1+\eta-(\mu+\eta)\mathrm{e}^{r_b(T-t)}},\frac{\theta S_t+(1+\theta)S_t\mathrm{e}^{r_a(T-t)}}{1+\eta-(\mu+\eta)\mathrm{e}^{r_a(T-t)}}\right] \tag{6}$$

Theoretically, when the futures price falls within the above no-arbitrage pricing interval, arbitrageurs cannot obtain risk-free profits due to the constraints of financing costs, transaction costs, and lending–borrowing rate differentials. Therefore, this interval can be regarded as the reasonable range for the futures price of carbon emission allowances in the actual market.

5.2.3 Policy-adjusted no-arbitrage pricing model

China's national ETS is still in a phase of frequent and incremental policy adjustments. Changes in the total cap, sectoral expansion, or reductions in the free-allocation ratio increase the expected scarcity of CEAs at the futures maturity date T, thereby raising the realizable spot value at delivery. The baseline interval in Section 5.2.2 implicitly treats the maturity spot as today's spot rolled forward only by financing and transaction costs. To align the model with the policy-created nature of CEAs, we adjust only the maturity-leg cash flow that depends on the resale (or repurchase) price at T, while keeping the trading structure, fee and margin conventions, and interest mappings unchanged.

Crucially, we follow Section 5.2.2 in which futures fees and margins are paid at t and then accrue with the financing leg until T: on the forward-arbitrage leg they are financed at the borrowing rate r_a; on the reverse-arbitrage leg they are embedded in the deposit earning r_b. This time structure produces the characteristic denominators $1+\eta-(\mu+\eta)\mathrm{e}^{r_a(T-t)}$.

Formally, we introduce two signed policy terms: $E_t\left[\Delta_p^+\right]$, the expected net policy-induced cash-flow relevant to the upper bound (forward arbitrage: long spot, short futures); $E_t\left[\Delta_{\mathrm{p}}^{-}\right]$, the expected net policy-induced cash-flow relevant to the lower bound (reverse arbitrage: short spot, long futures). Under tightening expectations (e.g., lower cap, delayed sectoral expansion, smaller free-allocation ratios), both terms are typically positive: they reduce the upper bound and raise the lower bound, compressing the no-arbitrage interval.

(1) Upper bound of policy-adjusted no-arbitrage pricing interval

To operationalize the policy-adjusted interval, we detail the two canonical arbitrage portfolios that underpin the upper and lower bounds. Throughout, the trading structure, fee and margin conventions, and interest-rate mapping strictly follow Section 5.2.2. The only departure is that the maturity-leg cash flow tied to the resale (or repurchase) of allowances at $T$is adjusted by a signed, expected policy term.

For the forward arbitrage portfolio, the trader buys spot CEAs and sells futures, financing the initial outlays at rate r_{a}. At maturity the position is unwound; because policy recalibrations alter the resale value of allowances, we add a signed policy term to the maturity cash flow. The cash flow process is shown in Table 5.

Table 5 Cash flows of the forward arbitrage strategy in CEAs futures (policy-augmented upper bound).

Arbitrage strategy	Cash flow at time t	Cash flow at maturity T
Buy CEAs spot	$-(1+\theta)S_t$	$(1-\theta)S_t$
Sell CEAs futures	$-(\mu+\eta)F_{i,T}$	$F_{i,T}-S_t+\eta F_{i,T}$
Borrow funds	$(\mu+\eta)F_{i,T}+(1+\theta)S_t$	$-\left[(\mu+\eta)F_{i,T}+(1+\theta)S_t\right]\mathrm{e}^{r_{\mathrm{a}}(T-t)}$
Policy adjustment	–	$-E_t\left[\Delta_{\mathrm{p}}^{+}\right]$
No-arbitrage equilibrium condition	$=0$	$\leqslant 0$

The upper bound of policy-adjusted no-arbitrage pricing interval for carbon allowance futures, $\overline{F}_{t,T}^{\text{policy}}$, is

$$F_{t,T}\leqslant\overline{F}_{t,T}^{\text{policy}}=\frac{\theta S_t+(1+\theta)S_t\mathrm{e}^{r_{\mathrm{a}}(T-t)}-E_t\left[\Delta_{\mathrm{p}}^{+}\right]}{1+\eta-(\mu+\eta)\mathrm{e}^{r_{\mathrm{a}}(T-t)}} \tag{7}$$

(2) Lower bound of policy-adjusted no-arbitrage pricing interval

For the reverse arbitrage portfolio, the trader sells spot and buys futures, depositing the net inflow at rate r_{b}. At maturity the spot is repurchased and the futures closed; policy recalibrations alter the replacement cost, which we model with a signed addition. The cash flow process is shown in Table 6.

The lower bound of the no-arbitrage pricing interval for carbon allowance futures, $\underline{F}_{t,T}^{\text{policy}}$, is

$$F_{t,T}\geqslant\underline{F}_{t,T}^{\text{policy}}=\frac{(1-\theta)S_t\mathrm{e}^{r_{\mathrm{b}}(T-t)}-\theta S_t+E_t\left[\Delta_{\mathrm{p}}^{-}\right]}{1+\eta-(\mu+\eta)\mathrm{e}^{r_{\mathrm{b}}(T-t)}} \tag{8}$$

Collecting the two bounds yields the policy-adjusted interval:

$$\left[\frac{(1-\theta)S_t\mathrm{e}^{r_{\mathrm{b}}(T-t)}-\theta S_t+E_t\left[\Delta_{\mathrm{p}}^{-}\right]}{1+\eta-(\mu+\eta)\mathrm{e}^{r_{\mathrm{b}}(T-t)}},\frac{\theta S_t+(1+\theta)S_t\mathrm{e}^{r_{\mathrm{a}}(T-t)}-E_t\left[\Delta_{\mathrm{p}}^{+}\right]}{1+\eta-(\mu+\eta)\mathrm{e}^{r_{\mathrm{a}}(T-t)}}\right] \tag{9}$$

Table 6 Cash flows of the reverse arbitrage strategy in CEAs futures (policy-augmented lower bound).

Arbitrage strategy	Cash flow at time t	Cash flow at maturity T
Sell CEAs spot	$(1-\theta)S_t$	$-(1+\theta)S_t$
Buy CEAs futures	$-(\mu+\eta)F_{i,T}$	$-(F_{i,T}-S_t)+\eta F_{i,T}$
Deposit funds	$-\left[(1-\theta)S_t-(\mu+\eta)F_{i,T}\right]$	$\left[(1-\theta)S_t-(\mu+\eta)F_{i,T}\right]\mathrm{e}^{r_{\mathrm{b}}(T-t)}$
Policy adjustment	–	$E_t\left[\Delta_{\mathrm{p}}^{-}\right]$
No-arbitrage equilibrium condition	$=0$	$\leqslant 0$

5.3 Empirical results of carbon futures pricing

In this section, Eqs. (3) and (6) are applied to calculate the theoretical prices of China's carbon emission allowance futures over the period from July 6, 2021, to June 4, 2025. To avoid the impact of futures contracts entering the delivery month, this study selects CEAF202512 as the representative contract for pricing analysis, with its value determined based on the national carbon allowance spot prices and other parameters.

The empirical dataset consists of the daily closing prices of CEAs in the National Carbon Market from July 6, 2021, to June 4, 2025, comprising a total of 929 observations, with data obtained from the CSMAR database.

For parameter estimation under the cost-of-carry model, S_t represents the daily closing price of CEAs, and the risk-free rate r is approximated by the one-year deposit rate over the same period. For parameter estimation under the no-arbitrage interval pricing model: S_t is the daily closing price of CEAs; regarding the CEA transaction fee rate θ, the National Carbon Market has not yet imposed transaction fees in order to enhance market activity. In addition, in the purchase and sale of carbon allowances, parties are theoretically subject to stamp duty. However, the Stamp Duty Law of the People's Republic of China only came into effect on July 1, 2022. Moreover, as carbon emission allowances are a new type of product and the National Carbon Market remains in its early stage of development, the stamp duty tax schedule under the Provisional Regulations of the People's Republic of China on Stamp Duty (issued on August 6, 1988) does not cover carbon allowances. Consequently, in current trading practice, taxation on carbon allowance transactions lacks explicit regulation. For the sake of simplification, this study does not consider stamp duty, and thus θ = 0 The transaction fee rate for CEA futures, μ is generally determined by the rules of the relevant exchange; here, we adopt the lower rate charged by the Hubei carbon forward and Shanghai carbon forward markets, i.e., 0.05%. The margin ratio for CEA futures η, is set at 10%. The risk-free deposit rate r_{b} is proxied by the one-year deposit rate, while the risk-free lending rate r_{a} is proxied by the one-year Loan Prime Rate (LPR). The parameter estimates are presented in Table 7.

Table 7 Summary of parameter estimates.

Parameter	Description
S_t	Daily closing price of CEAs
r	One-year deposit rate
θ	0
μ	0.05%
η	10%
r_{b}	One-year deposit rate
r_{a}	One-year loan prime rate (LPR)

Figure 6 presents the theoretical prices of carbon allowance futures calculated using the cost-of-carry model and the no-arbitrage interval pricing model. The results indicate that there is little difference between the two models: the upper bound of the no-arbitrage interval yields the highest price, while the cost-of-carry model and the lower bound of the no-arbitrage interval produce nearly identical prices.

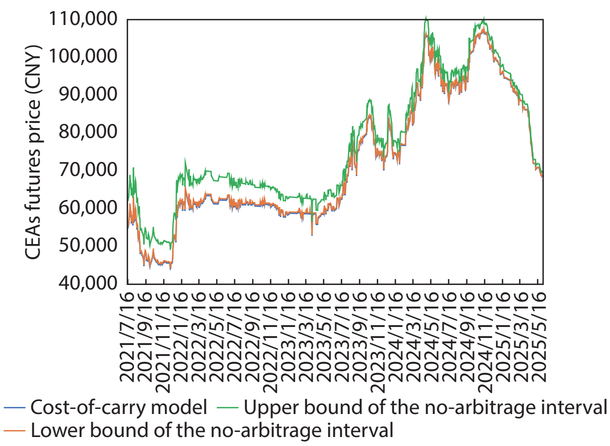

Fig. 6 Theoretical prices of CEAs futures.

As is clear from equations (6) and (9), the policy-adjusted no-arbitrage band differs from the baseline only through the expected policy cash-flow terms at maturity, $E_t\left[\Delta_{\mathrm{p}}^{+}\right]$ and $E_t\left[\Delta_{\mathrm{p}}^{-}\right]$, while the trading frictions and exponential denominators remain unchanged; as a result, the policy version mainly induces a modest shift of the band (lowering the upper bound and raising the lower bound), with little impact on interval width or our empirical conclusions except during pronounced tightening/loosening episodes.

6 Conclusions and implications

6.1 Conclusions

This paper, centered on the core objective of promoting the healthy development of China's National Carbon Market, addresses prominent issues such as insufficient liquidity in the carbon spot market, severe price volatility, and the absence of risk management instruments. It emphasizes the importance of introducing carbon futures and other derivatives into the National Carbon Market and conducts research on the contract design and theoretical pricing of CEA futures. The main research conclusions are as follows:

First, the current National Carbon Market, dominated by spot trading, exhibits a distinct "compliance-driven" characteristic, with low trading activity and difficulty in forming stable and effective carbon price signals. Drawing on the experience of mature international markets such as the EU ETS, the introduction of carbon futures contracts can effectively enhance market liquidity, improve the price discovery mechanism, and provide compliance entities with essential risk management tools, thereby improving overall market efficiency and strengthening emission reduction incentives.

Second, in line with the actual conditions of China's market at its early stage of development, this paper provides detailed design proposals for key contract elements such as trading units, delivery methods, contract months, as well as risk control mechanisms including daily price limits, margin requirements, and forced liquidation rules. These designs aim to ensure that the products can operate smoothly upon launch while effectively managing market risks.

Third, the results of these pricing models constructed in this study show a high degree of consistency, with the cost-of-carry model consistently falling within the no-arbitrage interval, and the policy adjustment mainly induces a modest inward shift (lowering the upper bound and raising the lower bound). This indicates that the model provides a reliable theoretical benchmark for the initial pricing of carbon futures, thereby contributing to the formation of reasonable market expectations.

6.2 Policy implications

Based on the above conclusions, and in order to further deepen the construction of the National Carbon Market and fully leverage the role of market mechanisms in achieving the "dual carbon" goals, this paper puts forward the following policy recommendations:

First, develop regulatory framework and mechanism design for the carbon futures market. It is recommended that regulatory authorities (the Ministry of Ecology and Environment and the China Securities Regulatory Commission) promptly clarify the positioning and attributes of carbon futures and introduce dedicated administrative measures and risk control guidelines for carbon futures trading, thereby providing robust institutional guarantees for their smooth introduction and standardized operation.

Second, actively diversify market participants by introducing a wider range of investors. The root cause of low market activity lies in the limited participation base (primarily compliance entities). It is suggested that qualified financial institutions and institutional investors be gradually allowed to participate in carbon futures trading[29], thereby significantly enhancing market liquidity and depth through the introduction of diverse risk preferences and trading strategies.

Third, steadily promote carbon financial derivatives innovation to build a multi-tiered carbon market system. Based on successfully launching carbon futures, further exploration of carbon options, forwards, and swaps should be undertaken to provide the market with more comprehensive and flexible risk management tools[30,31]. Ultimately, a multi-level carbon market system should be established in which spot, futures, and other derivative markets develop collaboratively and complement one another.

Fourth, strengthen market monitoring system to ensure the stable launch of the carbon futures market. The carbon market links the real economy with financial markets and is critical to both emission reduction objectives and financial stability. It is recommended that regulators establish a comprehensive market monitoring and early warning system, enabling timely and effective intervention, such as adjusting margin requirements or daily price limits, when abnormal volatility or excessive speculation occurs. This will ensure that carbon prices reflect true marginal abatement costs while preventing drastic market fluctuations.

6.3 Limitations and future research directions

While this paper provides an integrated framework for the contract design and theoretical pricing of CEA futures in China's national ETS, several limitations remain and point to promising avenues for future research.

First, the pricing framework in this study is built on no-arbitrage logic under a stylized representation of market frictions. However, China's national ETS is still characterized by limited participation, compliance-driven trading, and institutional constraints that may prevent arbitrage from operating smoothly. Future research could explicitly model market incompleteness and trading constraints (e.g., participation limits, restrictions on short positions, funding and margin constraints), and examine how these features affect pricing bounds, hedging effectiveness, and the term structure of carbon futures.

Second, while our policy-adjusted pricing component incorporates policy considerations, it does not fully capture the potentially stochastic, forward-looking, and asymmetric nature of policy risk and climate-related shocks in emerging carbon markets. Recent studies emphasize that climate risks and policy-related shocks can meaningfully affect commodity- and carbon-related markets and may propagate across sectors and futures markets[32–33]. Future work may extend the framework by modeling policy and climate risks as regime-switching or jump processes, or by linking such risks to compliance expectations and information arrivals. These extensions would allow researchers to quantify how policy and climate shocks interact with carbon prices over time and how risk premia may be embedded in futures prices.

Third, our descriptive diagnosis highlights liquidity issues and market frictions, yet these elements are not explicitly mapped into a formal liquidity or information premium within the pricing structure. A growing body of evidence shows that information frictions and news sentiment can materially affect commodity price dynamics and prediction, implying a potentially important channel for futures pricing and risk management[34]. Moreover, climate-change risk may transmit across carbon allowances and commodity futures markets through multiple channels, including expectations, hedging demand, and sectoral exposures[33]. Future studies could therefore incorporate liquidity premiums, information frictions, and cross-market transmission mechanisms into no-arbitrage interval pricing, and explore how thin trading, segmentation, inventory risk, and compliance-seasonality jointly shape the convenience yield and effective pricing bounds.

Overall, these extensions would deepen the analytical foundation of carbon futures pricing in young, policy-influenced markets and provide stronger quantitative guidance for the phased development of China's carbon derivatives ecosystem.

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Author contribution statement

Yuanyuan Zhang: conceptualization, methodology, formal analysis, writing – original draft, review & editing. Yuyan Weng: conceptualization, writing – review & editing, supervision, funding acquisition.

Data availability

The data are available from the corresponding author upon reasonable request.

Use of AI statement

None.

Declaration of competing interest

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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