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RESEARCH ARTICLE

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How to auction carbon emission allowances? A dynamic simulation analysis of spatiotemporal heterogeneity

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Abstract There is notable variability in carbon emission reduction efforts across different provinces in China, underscoring the need for effective strategies to implement carbon emission allowance auctions. These auctions, as opposed to free allocations, could be more aligned with the principle of "polluter pays." Focusing on three diverse regions — Ningxia, Beijing, and Zhejiang — this study employs a system dynamics simulation model to explore markets for carbon emissions and green certificates trading. The aim is to determine the optimal timing and appropriate policy intensities for auction introduction. Key findings include: (1) Optimal auction strategies differ among the provinces, recommending immediate implementation in Beijing, followed by Ningxia and Zhejiang. (2) In Ningxia, there's a potential for a 6.20% increase in GDP alongside a 21.59% reduction in carbon emissions, suggesting a feasible harmony between environmental and economic objectives. (3) Market-related policy variables, such as total carbon allowances and Renewable Portfolio Standards, significantly influence the optimal auction strategies but have minimal effect on carbon auction prices.

Keywords carbon allowances, carbon allowance auctions, carbon emissions trading, Renewable Portfolio Standard, system dynamics

1 Introduction

Climate change is a significant environmental challenge in the 21st century. In response to this issue, global actions are being taken toward achieving carbon peaking and carbon neutrality objectives. The Chinese government has committed to achieving a peak by 2030 and neutrality by 2060 by promoting the green transformation of its economic structure while balancing medium- and long-term economic growth targets with binding targets for reducing carbon intensity. A pivotal strategy entails the persistent advancement of high-level frameworks to realize the carbon peaking and carbon neutrality goals, along with the continual development and enhancement of policies for reducing carbon emissions.

In recent years, the Carbon Emissions Trading (CET) market has gained popularity as a means to accomplish carbon reduction targets because of its flexibility and cost-effectiveness (Wang et al., 2018). Such a market serves as a crucial avenue for China to reach its carbon peak. Within a CET market, Carbon Emission Allowances (CEAs) are traded among enterprises within a top-down carbon accounting and allocation framework. The valuation of CEAs, along with market supply and demand dynamics, determines the carbon price. China initiated its carbon trading system in 2011 through eight pilot carbon trading regions. On July 16, 2021, China formally launched its national carbon market.

The primary concern in establishing a unified CET market is the initial allocation of CEAs, serving as the foundation for achieving emission reduction targets while upholding economic fairness and efficiency objectives. On December 30, 2020, China's State Ministry of Ecology

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and Environment released “Implementation Plan for Setting and Allocating the Total Amount of Carbon Emissions Trading Allowances for 2019–2020 (Power Generation Industry),” which outlined a baseline method for determining the number of CEAs allocated to key emission units in the early stages of the national CET market. The summation of these allowances established the provincial total, which was subsequently aggregated to determine the national CEA total. It is noteworthy that all CEAs for 2019–2020 were allotted without charge.

In the initial phases, the prevalence of free allocations aimed to make CET more acceptable to enterprises; however, this approach exhibited several drawbacks. Pilot CET markets revealed that free allocations tended to lead to allowance wastage, feeble carbon pricing, and suboptimal trading (Yu et al., 2018). This was due to the fact that zero- or low-cost access is less likely to reflect the genuine external costs associated with carbon emissions in the carbon price (Weng et al., 2021).

The auctioning of CEAs represents a superior approach to allocate carbon emission rights. Enterprises can participate in CEA auctions, with the market determining the auction prices and the allocation of CEAs to each enterprise. This approach aligns more closely with the “polluter pays” principle while minimizing adverse effects and distortions within the CET market. Auction allocations empower enterprises to independently determine the CEA supply in the primary market, irrespective of the availability and reliability of their emission data (Abrell et al., 2022). Such autonomy contributes to guiding carbon prices, bolstering market liquidity, fostering technological advancements in carbon reduction, and mitigating regulatory shortcomings. Consequently, the introduction of CEA auctions represents a crucial step forward for China’s CET market, ensuring that carbon prices accurately reflect the costs associated with carbon emission reduction, thereby advancing the goals of carbon peaking and carbon neutrality (Cong and Wei, 2012).

A full auction implementation currently presents challenges in China due to potential losses (Hübler et al., 2014), and the transition to carbon auctions appears to be a distant prospect. Among the eight pilot markets, only Guangdong, Shanghai, and Hubei have ventured into auctioning allowances, despite policies permitting auction allocations throughout. Existing policies continue to emphasize the provision of allowances through free allocation.

The performance of the California carbon cap-and-trade (CA CAT) market in the United States (US) demonstrates that an initial free allocation approach can gradually transition to a higher proportion allocated through auctions (Schmalensee and Stavins, 2017). In the case of China, a mixed allocation model is expected to distribute carbon allowances during the transition to the carbon market. The mixed model entails allocating all or a majority of allowances for free at the initial stage to facilitate rapid enterprise acceptance of the CET. As the CET system matures, it can recover economic output losses (Xian et al., 2020; Wei et al., 2021), permitting a gradual increase in the proportion of CEA and a natural transition to a full carbon auction model.

The mixed model imposes specific requirements on policy planning, prompting the question: At which juncture in the CET market’s development should CEA auctions be implemented? This question is particularly critical to achieving the increasingly pressing 2030 and 2060 carbon targets. Implementing CEA auctions prematurely may exert substantial financial pressure on enterprises and hinder emission reduction efforts. Conversely, delayed or inadequately proportioned auctions may jeopardize the attainment of reduction targets. Hence, it is crucial to investigate the optimal timing and approaches for introducing CEA auctions.

China presently promotes a Renewable Energy Portfolio Standard (REPS) and Tradable Green Certificates (TGCs) concurrently with CET. These initiatives form crucial components of a new phase of power system reforms. REPS mandates that a specific percentage of electricity sales or purchases by electricity enterprises originate from renewable energy sources. TGC enables cross-regional trading of clean energy electricity to mitigate regional resource disparities (Zeng et al., 2022). China’s renewable energy resources are concentrated in the north-western and south-western regions, making the policy conducive to cross-provincial trade in clean energy (Feng et al., 2018). The CET system discourages conventional energy generation, while RPS and TGC systems increase external revenues from renewable energy, thereby promoting its production (Huang et al., 2020; Yu et al., 2021). The interplay between CET and TGC directly influences market participants’ decisions, potentially fostering competition within the power industry. Consequently, the study of carbon auctions should consider RPS and TGC, along with strategies for coordinating these policies to maximize their effectiveness.

This study has developed a regional carbon emission simulation model including the CET and TGC markets to explore the most efficient approach to introducing CEA auctions. Additionally, a scenario analysis has been conducted, evaluating policy elements such as carbon prices and renewable energy portfolios, with resulting recommendations for a well-structured and efficient transition to auctions within China’s CET market.

The remainder of this paper is organized as follows: Section 2 reviews pertinent literature, Section 3 introduces the methodology and research framework, Section 4 outlines the construction and validation of the system dynamic (SD) model, Section 5 discusses the results of the model’s simulation and scenario analysis. Finally, Section 6 presents the conclusions and policy implications.

2 Literature review

This section reviews and compares past studies on CEA allocations and the effects of regional heterogeneity. We identify the gaps in knowledge and explore ways to fill them.

2.1 Carbon emission allowance auctions

Playing a crucial role in the evolving efficiency and economic dynamics of China's CET market, the allocation of CEAs has attracted significant scholarly attention. Wang et al. (2019a) developed a CEA allocation model that incorporated principles of fairness and efficiency, with the objective of minimizing fairness deviation. Yang et al. (2020) devised a CEA allocation framework that considered both equity and efficiency through a multi-objective nonlinear programming model, determining optimal CEA allocations for all 30 Chinese provinces. Meanwhile, He et al. (2021) scrutinized 15 allocation schemes, evaluating their effects on economic growth and energy conservation, ultimately advocating for a scheme that harmonizes efficiency and affordability. These studies primarily focused on allocation methods predicated on free allocation.

In contrast, limited attention has been directed toward CEA auctions, despite their effectiveness in pricing and allocation. Auctions possess attributes such as information stimulation and allocation effectiveness, which surpass the advantages of free allocations (Narassimhan et al., 2018). CEA auctions offer greater flexibility in cost distribution and stronger incentives for innovation, thereby fostering carbon emissions reduction, optimizing industrial structures, and mitigating adverse selections by emitters (Cramton et al., 2002; Wu et al., 2016). Furthermore, auctions enhance the efficiency of the CET market while adhering to the equity principle. CEA auctions, when integrated into macro-regulations, furnish an effective market-based instrument within China's Emissions Trading System (ETS) (Wang et al., 2019b), with carbon prices serving as an effective market regulator exclusively under auction rules (Zhang et al., 2021).

Studies conducted internationally have provided insights into the evolution of CEA auctions and may offer valuable reference points for China. As carbon markets continue to mature, an increasing number are expected to adopt CEA auctions, gradually phasing out free allocations. Notably, during the third phase of the European Union (EU) ETS, CEA auctions were introduced to counter windfall profits accrued by companies through free allocations (Carratù et al., 2020). Presently, major carbon markets worldwide, including the EU ETS, the US Regional Greenhouse Gas Initiative (RGGI), the US Western Climate Initiative (WCI), the CA CAT, the Quebec carbon market in Canada, and the Korean carbon market, predominantly rely on CEA auctions. In most EU ETS member nations, 100% of allowances for power generation facilities are subject to auction.

Zhang et al. (2019) reviewed the auction mechanisms in various carbon markets, including the EU, California, Australia, and China's pilot carbon markets. They subsequently outlined proposals for China's auctions concerning factor design, platform construction, and fund management. Qi et al. (2019) investigated the global carbon financial market and analyzed the EU's CEA auction mechanism, specifically examining the auction ratio, auction frequency, and related factors. Their study serves as a valuable reference for China's carbon market development. These collective efforts have facilitated the delineation of a generalized trajectory for carbon market evolution. Utilizing the EU ETS as a benchmark, a CEA auction system has been formulated, featuring four main stages, as presented in Table 1. This system represents a pragmatic and secure approach for China to progressively implement CEA auctions.

Numerous studies have concentrated on identifying the optimal mechanisms for CEA auctions and comparing different auction rules. Cong and Wei (2012) conducted a comparative analysis including uniform price, discriminatory price, and English clock auctions, evaluating aspects such as carbon prices, auction efficiency, demand withholding, and power supply fluctuations. Wang et al. (2016) explored the allocation efficiency of various CEA auction mechanisms, revealing that different auction rules could prompt bidders to adopt distinct bidding strategies. Tang et al. (2017) proposed a multi-agent-based ETS simulation model for designing a CEA auction in China, suggesting that the uniform-price design struck a moderate balance in terms of both economic consequences and emission reduction. In contrast, He et al. (2021) found that the Maskin auction mechanism entailed the highest spending from a fixed subsidy budget, resulting in the

Table 1 Development of EU carbon market (Schiavo, 2012)

Phase	Time	Contents
Pilot phase	2005–2007	CEAs were mainly allocated free of charge and the CEAs from auctions were no more than 5%
Optimization phase	2008–2012	The proportion of CEAs from auctions was gradually increased to 10%
Maturity phase	2013–2020	The proportion of CEAs from auctions will exceed 50% of the EU market-wide CEAs, with all CEAs from auctions in the power sector and more than 70% in the manufacturing sector by 2020
Promotion phase	2021 and so far	Free allocation will be nearly canceled

largest emissions reduction; however, it incurred a higher per-unit emission reduction cost when compared to other auction mechanisms for allocating subsidies. Avval et al. (2021) employed multi-agent Q-learning to compare uniform and discriminative price methods, concluding that the former exhibited more advantages in terms of firm profits and auction efficiency.

Numerous scholars have devised auction rules or models tailored for the CET market. Chen and Meng (2016) considered the carbon budgets of specific entities and proposed a revenue allocation scheme predicated on estimating marginal abatement costs (MAC) using bidders' information. Ramli et al. (2017) adopted a mechanism design approach to develop a model for a Carbon Permit Auction in Malaysia. Wang et al. (2020a) integrated firms' bidding strategies and governmental regulations to propose a multi-round auction model aiming for higher and more stable clearing prices that encouraged firm participation. Wang et al. (2020b) centered their focus on designing the proportion of auction allocation for the initial allowance, employing a multi-agent model to explore interactions between the CET market and medium- and long-term electricity markets. Analyzing auction ratio settings, Liu et al. (2016) found that higher auction rates led to increased carbon emission abatement costs. A 5% CEA auction rate added a substantial burden to China's electric power generation sector, potentially hindering progress toward increased auctioning. Luo et al. (2022) used the Asia-Pacific Integrated Model/Enduse Model to identify the optimal combination of CEA auction ratios and prices in the Guangdong–Hong-Kong–Macao Greater Bay Area (GBA), noting that carbon emission constraints only became effective when the auction ratio reached 50%. Thus, a low-carbon transition in the GBA's power sector could be achieved solely with a 100% auction ratio.

While few studies have explored the ideal mechanisms for advancing carbon allowance auctions, Weng et al. (2021) proposed a blend of free allocation and carbon auctions within the power industry in the existing CET market. They recommended that auctioned allowances should exceed 50% by 2025 and reach 100% through auctions or other means by 2030. However, these recommendations were based on the author's personal experience rather than empirical findings.

Some studies have examined corporate strategies within CEA auctions. Zeng et al. (2010) introduced auction allocation into the CET market to analyze corporate profits resulting from diverse strategies employed by companies with varying emission ratios. Dormady et al. (2019) found that short-term profits were lower in a consignment auction compared to a non-consignment auction market. In the consignment model, firms were less likely to secure the necessary permits for program compliance, necessitating overstatements of their demand quantities in auctions.

2.2 Regional spatiotemporal heterogeneity

China's extensive geographical expanse and substantial regional disparities underscore the complexity and significance of CEA allocation. Regional variations in both the cost and potential for carbon reduction necessitate nuanced allocation strategies. Notably, the cost of carbon reduction warrants a differentiated approach, particularly in light of the economic disparities and varying carbon emission efficiencies among China's regions. Central and western provinces, characterized by underdeveloped economies and relatively lower carbon emission efficiencies, should witness a reduction in their allocated CEAs, as proposed by Zhan (2022). Conversely, eastern coastal provinces should see an increase in their CEAs.

China's high energy-consuming industries exhibit significant disparities in MACs, which exhibit a gradual decline from east to west (Jiang et al., 2018; Xian et al., 2022). Moreover, when assessing the potential for carbon reduction, it becomes evident that the eastern region boasts higher carbon productivity compared to the western region (Sun et al., 2023). This elevated carbon productivity affords eastern provinces greater latitude for investment in carbon reduction initiatives. Nevertheless, western regions also possess advantages in emissions reduction. Abundant local renewable resources enable the western region to undertake additional emission reduction responsibilities by enhancing the utilization of renewable resources, thereby bolstering long-term economic development (Tan et al., 2020).

To summarize, provinces in western China confront comparatively fewer challenges in terms of emission reduction in contrast to their counterparts in the central and eastern regions (Cui et al., 2021). Consequently, each province should shoulder a distinct burden for emission reduction, reflecting the regional disparities. Carbon reduction policies must consider these regional distinctions, necessitating the formulation of common yet differentiated strategies to equitably achieve national carbon objectives.

2.3 Literature review and research gaps

The majority of research pertaining to carbon allowance auctions has predominantly focused on their implementation, with limited attention given to recommendations for their development. Consequently, there exists a critical need for research that integrates simulation and evaluation techniques to determine the optimal approach for implementing carbon quota auctions. Furthermore, it is essential to identify effective, synergistic policies involving the CET and TGC to foster the sustainable development of China's carbon trading market.

In response to these knowledge gaps, this study systematically amalgamates industry characteristics, CEA auction implementation strategies, and policy designs into a comprehensive conceptual framework, as illustrated in Fig. 1. This framework comprises four layers: industry characteristics, policy scenarios, policy results, and policy analysis. The layer of industry characteristics pertains to mechanisms pertinent to the power industry. Policy scenarios are established based on considerations related to the CET and TGC markets, alongside relevant regional attributes. Policy results are derived from simulations conducted within the SD model, including economic, energy, and policy subsystems. The policy analysis layer includes the evaluation of environmental and economic benefits resulting from the scenarios, which are compared and assessed using the Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS) methodology. By analyzing these interconnected layers, meaningful conclusions can be drawn, leading to the formulation of valuable policy recommendations. This theoretical framework possesses the potential to deliver substantial value by offering policy guidance that may facilitate the transformation and advancement of China’s carbon market.

This study directed its focus toward addressing three principal inquiries through model simulations and analyses. (1) First, it sought to determine the optimal timing for implementing CEA auctions to achieve the most favorable economic and environmental results. To explore this, a series of scenarios were formulated for simulation. (2) Secondly, the study aimed to assess how resource spatiotemporal heterogeneity impacts the optimal timing of CEA auction implementation. This was accomplished through a comparative analysis involving three representative provinces. (3) Lastly, the study examined how the optimal implementation timing might evolve in response to the future development of CET and TGC policies. A sensitivity analysis was conducted, considering three pertinent parameters: carbon price, total CEA amount, and the proportion of renewable energy absorption.

This study contributes significantly to the field in several key ways. (1) First, it approaches CEA auctions from the perspective of policy implementation, distinguishing itself from prior research that predominantly focused on the final configuration of carbon quota auction policies. By addressing the transition from free allocation to auction, it offers valuable insights into achieving the optimal approach for implementing carbon auctions, thereby providing theoretical underpinning for the transformation of the CET market into a more mature and efficient entity. (2) Secondly, it employs an SD simulation to analyze CET policy, integrating both the CET and TGC markets and considering their potential evolution and adjustments in the future. This approach enhances the model’s alignment with the complexities of the real-world scenario. (3) Lastly, the study examines the spatial and temporal heterogeneity inherent in policy formulation, accounting for regional disparities in economic, social, and resource attributes. This nuanced approach yields localized and more precise estimations, enhancing the relevance and specificity of the study’s findings.

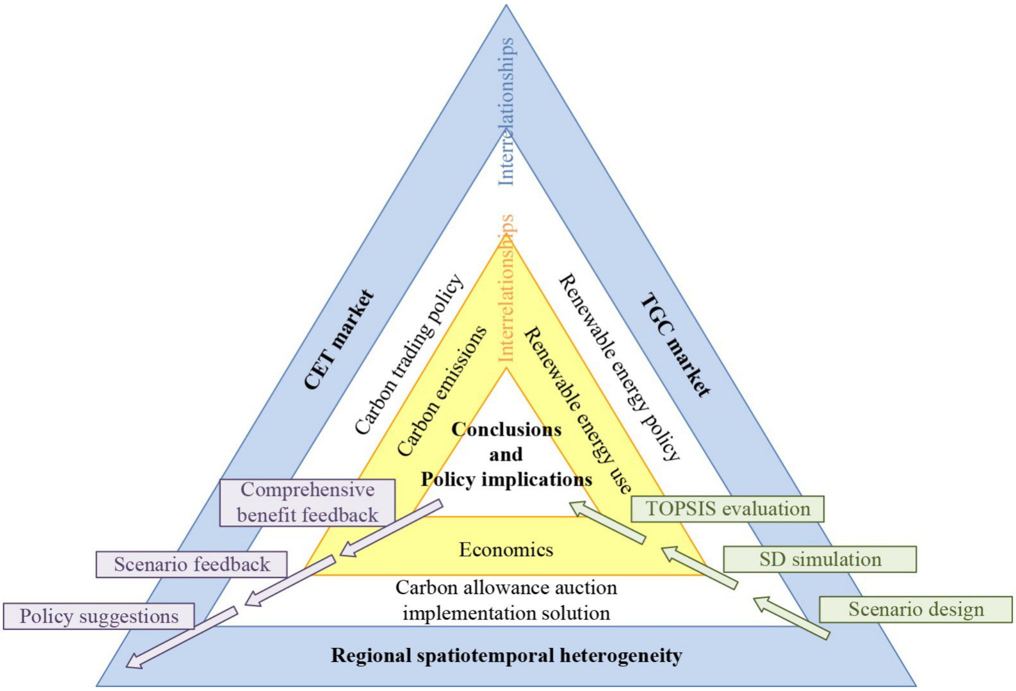

Fig. 1 Research concept framework.

3 Methodology

SD and TOPSIS were employed to connect the outermost industry characteristics layer to the innermost policy analysis layer in Fig. 1. The methodology is described below in detail.

3.1 System dynamic method

The SD method is a valuable approach for examining the dynamic changes and causal relationships within complex systems (Dong et al., 2012). Forrester (2007) provides a comprehensive history of the SD method, which is highly effective in addressing complex systems and has found extensive application in the domain of carbon emission reduction. It has been instrumental in tracking carbon emission trends and simulating the results of carbon emission reduction efforts (Du et al., 2018; Wu et al., 2022; Luo, 2023). The SD method involves defining the study's objectives, delineating system boundaries, formulating causal connections among system factors, and subsequently simulating various scenarios.

The carbon emission system within the power sector is inherently complex, including a multitude of economic, energy, and environmental elements. Employing qualitative analysis, we identified the system boundaries and constituent elements, facilitating the construction of a comprehensive SD model that includes regional carbon emissions, particularly within the context of the CET and TGC framework. This model served as a pivotal tool for investigating the optimal timing for CEA auction implementation and evaluating the effect of crucial policy parameters. However, it is important to note that the SD method alone may not provide an entirely precise evaluation of simulation results. To address this limitation, we integrated the TOPSIS method into our analysis process.

3.2 TOPSIS method

TOPSIS is a method designed to rank the merits of multiple evaluated objects based on their proximity to optimal and inferior solutions (Hwang et al., 1981). The optimal solution is the one that is simultaneously closest to the ideal result and farthest from the inferior one. This method is widely employed and effective in the domain of multi-objective decision analysis and has made substantial contributions to research on carbon market maturity, risk assessment, and other dynamic aspects (Liu et al., 2019; Zhu et al., 2021).

In this study, the TOPSIS method was utilized to evaluate each scenario and determine the most favorable implementation scheme for CEA auctions. However, to conduct a comprehensive dynamic analysis of these schemes, particularly in the context of determining the optimal timing for auction implementation, the TOPSIS method alone proved insufficient. Therefore, we employed a TOPSIS method that is based on the system state obtained from the SD analysis. The primary indicators used to assess the scenarios were CO_2 emissions and Gross Domestic Product (GDP). Achieving accurate results was contingent upon assigning appropriate weights to these indicators, as CEA auctions necessitate a delicate balance between environmental and economic benefits.

It is noteworthy that carbon reduction and economic development are often at odds, as the former often entails some form of economic sacrifice. Consequently, we carefully weighed these two factors to determine an optimal equilibrium. Subsequently, the TOPSIS method was employed to evaluate the results. Initially, the two indicators were normalized using the min-max standardization method. Notably, CO_2 emissions represent a cost-based variable, and the objective was to minimize its value while simultaneously maximizing GDP. The normalization formula for CO_2 emissions is as follows:

$$y_i = \frac{\max(x) - x_i}{\max(x) - \min(x)}. \tag{1}$$

GDP is a revenue-based variable, so the larger the indicator, the better is the effect. Its normalized formula is:

$$y_i = \frac{x_i - \min(x)}{\max(x) - \min(x)}. \tag{2}$$

The distance of each solution from the optimal solution $d(s_i, S^+)$ is:

$$d(s_i, S^+) = d_i^+ = \sqrt{\sum_{j=1}^{n} \left(y_{ij} - Y_j^+\right)^2}. \tag{3}$$

The distance of each solution from the worst solution $d(s_i, S^-)$ is:

$$d(s_i, S^-) = d_i^- = \sqrt{\sum_{j=1}^{n} \left(y_{ij} - Y_j^-\right)^2}. \tag{4}$$

The economic and environmental aspects are considered together, so we give equal weights to both indicators. The final scoring of each scenario C_i is:

$$C_i = \frac{d_i^-}{d_i^- + d_i^+}. \tag{5}$$

Through the implementation of the TOPSIS evaluation process, this study comprehensively considered the economic and environmental impacts resulting from the carbon quota auction. The findings offer a scientifically grounded foundation for the selection of the most suitable auction program.

3.3 Methodology flow chart

The integration of the SD model and the TOPSIS method facilitated the simulation and analysis of policy scenarios concerning CEA auction implementation. This comprehensive approach enabled the evaluation of the associated benefits and yielded valuable policy recommendations aimed at driving the transformation and development of China's CET market.

Figure 2 illustrates the methodology flowchart, comprising two primary stages. The first stage outlines the policy scenarios and conducts simulation based on these scenarios. The second stage involves the utilization of the TOPSIS model to assess the holistic benefits associated with each scenario. This process culminates in the identification of effective strategic proposals and the formulation of policy recommendations.

4 Model construction

4.1 Causal and stock-flow diagrams

The SD model includes four distinct subsystems: CET, TGC, economy, and energy and emissions. Within the CET subsystem, variables such as the auction proportion, total CEAs, carbon trading price, and carbon trading volume are considered. In the TGC subsystem, key variables include the proportion of renewable energy and electricity consumption, TGC price, and TGC trading volume. The economy subsystem takes into account GDP, firm profit, and carbon emission cost. Finally, the energy and emissions subsystem includes variables such as CO_2 emissions, CO_2 emission coefficients, energy efficiency, electricity consumption, and renewable energy and electricity consumption.

Figure 3 shows a causal loop diagram of regional carbon emissions. The four main feedback loops are as follows.

(1) GDP → (+) energy efficiency → (–) CO_2 emissions → (+) environmental governance costs → (+) GDP

Economic development stimulates technology investments within the power sector, leading to reduced CO_2 emissions compared to traditional power generation methods. This reduction in carbon emissions, in turn,

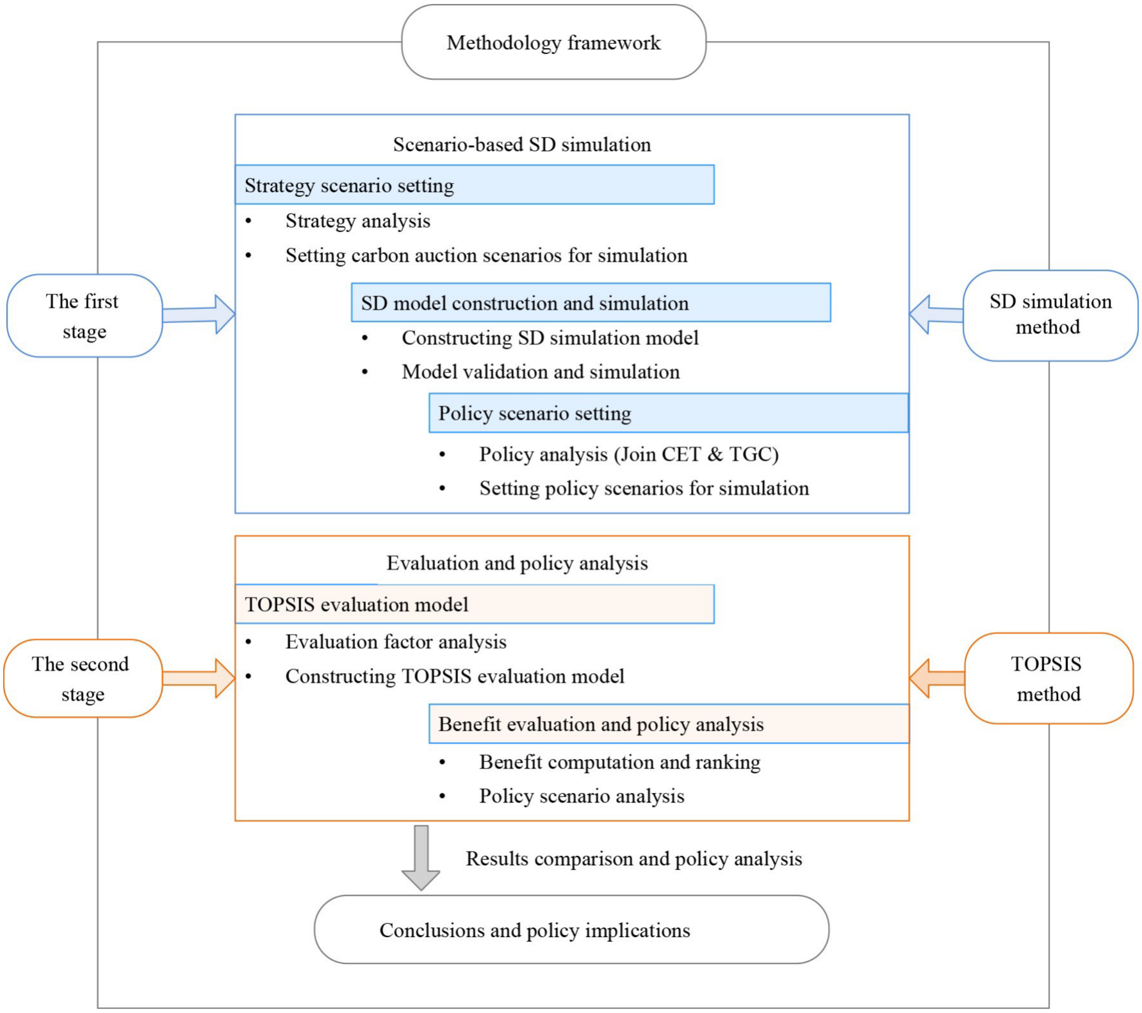

Fig. 2 The research framework.

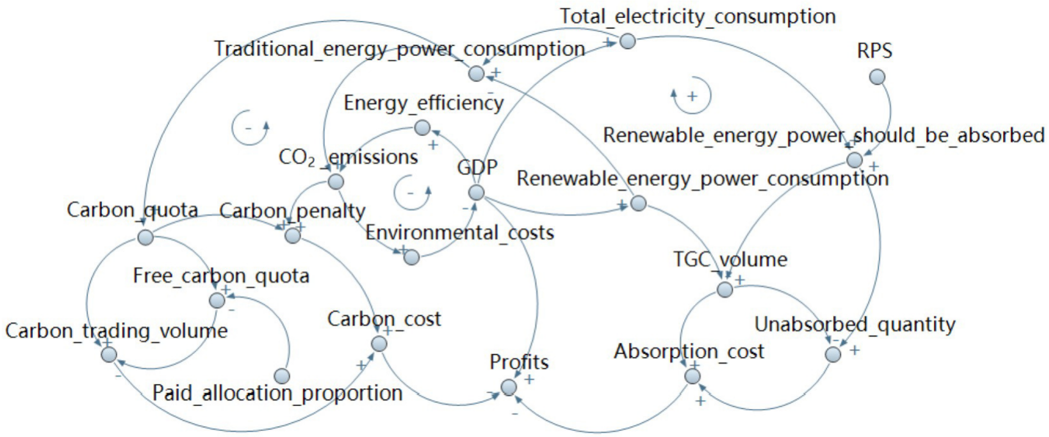

Fig. 3 Causal diagram of regional carbon emissions.

results in decreased environmental pollution and the associated costs of environmental management. Consequently, these changes have a favorable effect on GDP.

(2) GDP → (+) total electricity consumption → (+) renewable energy to be absorbed → (+) unabsorbed quantity → (+) absorption cost → (–) profits → (+) GDP

An increase in GDP corresponds to a rise in electricity demand. To meet the requisite percentage of renewable electricity consumption, the province must absorb more renewable energy. Consequently, both the consumption of renewable energy and the unmet consumption of CEA in that province increase. This escalation in absorption costs exerts downward pressure on profits and results in a reduction in GDP.

(3) GDP → (+) energy efficiency → (–) CO$_2$ emissions → (+) free CEAs → (–) carbon trading → (+) carbon costs → (–) profits → (+) GDP

As economic development progresses, the power sector's energy efficiency improves, leading to reduced CO$_2$ emissions. Consequently, the quantity of freely allocated CEAs decreases. This decrease in free CEAs, coupled with a substantial increase in carbon trading volume, substantially elevates emissions costs. The subsequent decline in profits serves as a hindrance to GDP growth.

(4) GDP → (+) renewable energy consumption → (–) TGC trading volume → (+) absorption cost → (–) profit → (+) GDP

With an upward trajectory in the overall level of economic development, technology advancement and heightened environmental awareness become more prevalent. This leads to increased consumption of renewable electricity, a reduction in TGC transactions, and lower costs associated with renewable electricity consumption. Ultimately, the diminished absorption costs contribute to higher profits, thereby exerting a direct and positive influence on the overall GDP.

The stock-flow diagram depicted in Fig. 4 is a derivative of the causal loop diagram featured in Fig. 3. It is employed to facilitate a more complex quantitative analysis of the system.

4.2 Main variables and parameters

This study conducted region-specific simulations of policy scenarios, selecting provinces that represent distinct economic levels and resource conditions for data collection and model construction. Typically, regions with more developed economies tend to possess fewer resource endowments. Figure 5 displays the GDP along with the types of photovoltaic and wind energy resources in each province (excluding Xizang) for the year 2021. Both types of resources are categorized into resource areas: Classes I, II, III, and IV (for wind resources only), with Class I representing the most resource-rich areas. Based on their levels of economic development and potential for renewable energy development, these provinces can be broadly classified into three types of areas: "high–low" areas characterized by a high economic level but low potential for renewable energy development, "medium–medium" areas with a moderate economic level and renewable energy development potential, and "low–high" areas with a low economic level but a high potential for renewable energy development. Each of these areas was subjected to simulation and analysis, enabling the formulation of precise and tailored policy recommendations.

Upon careful consideration of data availability, three provinces (cities) were chosen as representatives for data collection and model construction: Ningxia to represent the "low–high" region, Beijing for the "medium–medium" region, and Zhejiang for the "high–low" region. The SD model utilized data from their respective CET and TGC markets, which were sourced from the China Carbon Emissions Trading Network, *China Statistical Yearbook*, China Green Power Certificate Subscription and Trading Platform, and the *National Renewable Energy Development Monitoring and Evaluation Report*. Table 2

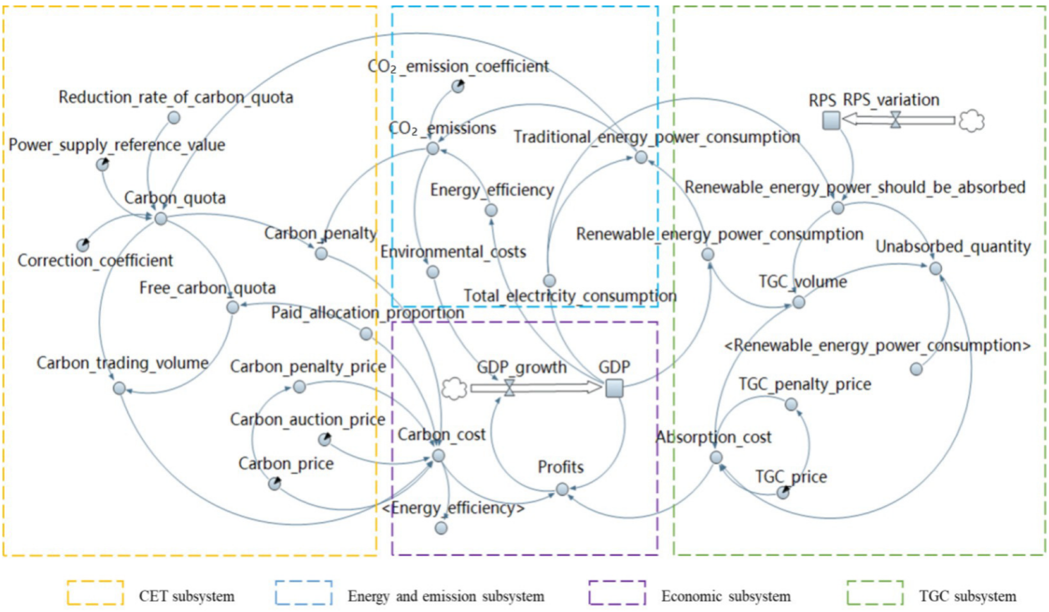

Fig. 4 Stock-flow diagram.

provides a comprehensive overview of the relevant variables and parameters, as well as their respective sources.

4.3 Model validation

The initial step in the analysis involved the use of AnyLogic software to construct a preliminary SD model, ensuring that it operated without errors. Subsequently, the model underwent rigorous validation testing to eliminate structural and quantitative discrepancies that might compromise the reliability of predictions. After confirming the model's compliance with the conditions for simulation analysis, the actual simulation was conducted.

The validity assessment relied on key indicators, including the GDP, renewable energy consumption, and electricity consumption of Ningxia, Beijing, and Zhejiang. It compared the simulation results for the period 2015–2019 with the real-world data to evaluate the model's precision and accuracy. The comparison, as presented in Table 3, demonstrated that the average absolute error for simulated GDP was 1.17%, with a maximum error of −4.64%. Similarly, the average error for renewable energy and electricity consumption was 1.70%, with a maximum error of −6.84%. All absolute errors remained below 7%, falling within an acceptable range. These results affirm that the model closely aligns with the actual environmental and economic developments in Ningxia, Beijing, and Zhejiang, facilitating progression to the subsequent phase of analysis.

4.4 Scenario designs

To investigate the optimal timing for implementing CEA auctions, this study devised 15 distinct scenarios, denoted as S1 to S15, each characterized by varying implementation timelines. These scenarios followed a gradual, two-year stepwise progression, incrementally increasing the proportion of auctioned CEAs from 2022 to 2030. The allocation proportions for each phase were guided by the experience of the EU ETS market. Phase I involved a 100% free allocation of CEAs, Phase II introduced a trial allocation with 10% of CEAs auctioned, Phase III saw an escalation of the auction proportion to 50%, and Phase IV culminated in the complete auctioning of all CEAs. To assess the effectiveness of CEA auctions, a baseline scenario (Business as Usual, BAU) was established, featuring full free allocation of CEAs. For detailed specifications, please refer to Table 4.

Simulation Scenarios A1 to C2 were devised to assess the effects of varying levels of RPS and CET policies on the timing of CEA auction implementation in Ningxia, Beijing, and Zhejiang. Scenarios A1 to A4 examined the consequences of fluctuations in carbon prices, specifically when the carbon price: (1) declines by 20%, (2) decreases by 10%, (3) rises by 10%, and (4) increases by 20% from the current price. To align with the primary objective of efficient carbon emission reduction, alterations in the total quantity of CEAs were determined by gradually diminishing the total CEA amount, simulating market participants' emission reduction actions. The rate of reduction escalated accordingly. Therefore, Scenarios B1 to B3 established annual reductions of 1%, 2%, and 3% in the total CEAs. In response to the directives from the National Development and Reform Commission (NDRC) for the three provinces serving as benchmarks, each with different RPS values, scenarios for increasing the RPS were analyzed. For precise scenario settings, please refer to Table 5.

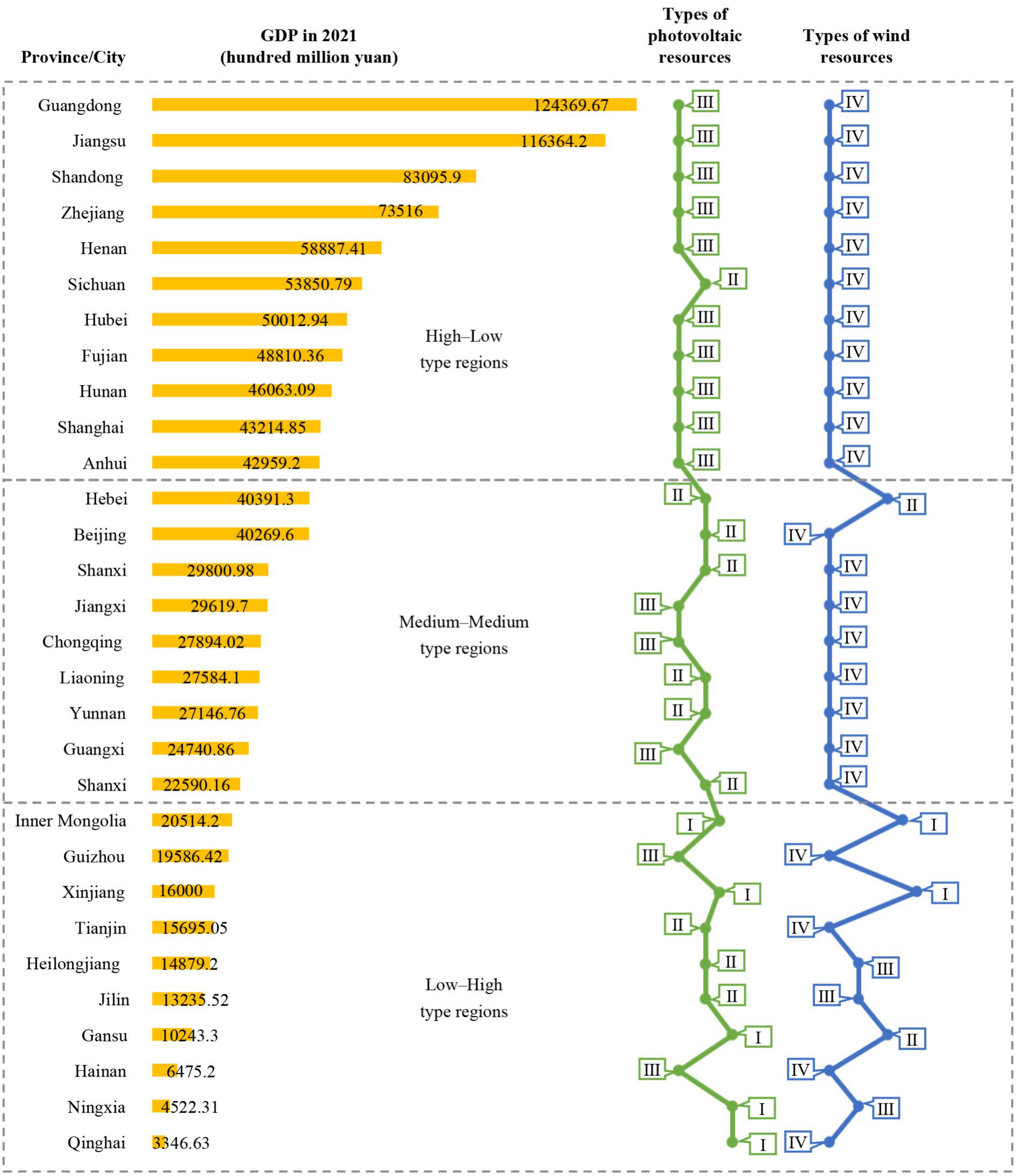

Fig. 5 Provincial economic level and resource endowment.

5 Results and discussion

Following model validation, scenario simulations were executed for the three provinces, as outlined in Section 2.4. Various variables, including GDP, renewable electricity consumption, carbon dioxide emissions, and carbon trading volumes, were analyzed and compared. The subsequent sections present an analysis of the model simulation data for Ningxia, followed by Beijing, and finally, Zhejiang.

5.1 Simulation results

5.1.1 Simulation results of Ningxia

Figure 6 illustrates the CO_2 emissions in Ningxia across the 15 scenarios. Comparing these scenarios to the baseline

Table 2 Settings of the main variables and parameters

Type	Factor	Unit	Value/Equation	Data sources
Constants	CECoef	t/TCE	1.229	MEE
	TGC price	yuan/a	202.9	NCETN
	Carbon price	yuan/t	62.1	NCETN
	PSREF	/	8.485	NDRC
	CorrCoef	/	1.0374	NDRC
Flows	GDP growth	BCNY	7.880 + 0.004 × Profits – 0.0004 × EnvCost	NBS
	RPS variation	/	TGC policy (Time)	Endogenous
Stocks	GDP	BCNY	$\mathrm{d(GDP)}/\mathrm{d}t$ = GDP growth	NBS
	RPS	/	$\mathrm{d(RPS)}/\mathrm{d}t$ = RPS variation	MEE
Variables	Profits	BCNY	0.1 × GDP – 0.1 × AbsCost	Endogenous
	EE	TCE/BKWH	$(22-15e^{-0.925+0.000136\mathrm{GDP}})/(1+e^{-0.925+0.000136\mathrm{GDP}})$	NBS
	RECsm	GWH	480.32 × log(GDP) – 3703.7	NBS
	TECsm	GWH	TCsm – RECsm	NBS
	EnvCost	BCNY	0.0258 × CE – 78.215	MEE
	CE	10 kt	TECsm × CECoef × EE	NBS
	REAbs	GWH	TCsm × RPS	MEE
	TVol	billion	(REAbs – RECsm)/10000	Endogenous
	UnQty	billion	(REAbs – RECsm)/10000 – TVol	Endogenous
	AbsCost	BCNY	TVol × TGC price – UnQty × TPEN price	Endogenous
	TPEN price	yuan/a	4 × TGC price	Endogenous
	Free CEA	10 kt	CE × Free ratio	Endogenous
	CVol	10 kt	Total CEA – Free CEA	Endogenous
	CPEN	10 kt	CE – Free CEA – CVol	Endogenous
	CECost	BCNY	CVol × Carbon price + CPEN × CPEN price	Endogenous
	CPEN price	yuan/t	4 × Carbon price	Endogenous

Table 3 Validity test results

	Year	GDP (billion yuan)			Renewable energy electricity consumption (billion kW·h)		
		Fitted value	Actual value	Error	Fitted value	Actual value	Error
Ningxia	2015	293.4517	291.177	0.78%	11.6363	11.8	–1.39%
	2016	312.6148	316.859	–1.34%	16.9842	16.9	0.50%
	2017	332.5961	344.356	–3.42%	20.9675	20.6	1.78%
	2018	353.3388	370.518	–4.64%	23.3821	23.747	–1.54%
	2019	374.8553	374.848	0.00%	24.0348	23.1	4.05%
Beijing	2015	2342.0592	2301.459	1.76%	7.2097	7.2	0.13%
	2016	2570.7622	2566.913	0.15%	9.4502	9.1	3.85%
	2017	2820.8635	2801.494	0.69%	11.4932	11.1	3.54%
	2018	3094.3155	3031.998	2.06%	13.2401	13.342	–0.76%
	2019	3393.4213	3537.128	–4.06%	14.5686	14.1	3.32%
Zhejiang	2015	4394.273	4288.649	2.46%	8.7993	8.4	4.75%
	2016	4804.552	4725.136	1.68%	12.8563	13.8	–6.84%
	2017	5250.605	5176.826	1.43%	17.7255	17.6	0.71%
	2018	5735.449	5619.715	2.06%	23.5598	23.956	–1.65%
	2019	6262.885	6235.174	0.44%	30.5473	31.9	–4.24%

Table 4 Scenario settings of implementation time

Scenarios	Phase II	Phase III	Phase IV
BAU	–	–	–
1	2022	2024	2026
2	2022	2024	2028
3	2022	2024	2030
4	2022	2026	2028
5	2022	2026	2030
6	2022	2028	2030
7	2022	2030	–
8	2024	2026	2028
9	2024	2026	2030
10	2024	2028	2030
11	2024	2030	–
12	2026	2028	2030
13	2026	2030	–
14	2028	2030	–
15	2030	–	–

scenario where all CEAs are freely allocated, an increase in the proportion of auctioned CEAs significantly contributes to reducing CO_2 emissions in Ningxia. Notably, in Scenarios 1–10, and 12, Ningxia achieves its carbon emission peak prior to 2030. Conversely, the emission peak is not reached in Scenarios 7, 11, 13, 14, and 15, as they do not progress to the fourth stage of the carbon market, meaning they do not fully transition to a complete auction-based CEA allocation.

Subsequently, we scrutinized the 10 scenarios that resulted in a carbon emission peak in Ningxia, constituting the best selection set. We then assessed their environmental and economic advantages to determine the optimal timing for the CEA auctions. Table 6 displays the evaluation scores computed by TOPSIS for all the alternative scenarios.

Table 6 clearly indicates that the optimal timing for the introduction of CEA auctions corresponds to Scenario 5. This scenario involves entering Phase II in 2022 with a 10% auction allocation, transitioning to Phase III in 2026 with a 50% auction proportion, and finally reaching Phase IV in 2030 when full CEA auctions are implemented. Figure 7 provides a comparison of the simulation results between this optimal scenario and the baseline scenario. The graph illustrates a substantial decrease in CO_2 emissions in Scenario 5, with a peak in 2022. Additionally, there is a reduction in GDP, but carbon trading volumes show a significant increase, indicating a more dynamic carbon trading market.

5.1.2 Simulation results of Beijing

Figure 8 illustrates the trends in CO_2 emissions and GDP growth in Beijing across the 15 scenarios. After careful consideration, it is evident that Scenarios 1, 2, 3, and 4 lead to a peak in carbon emissions before 2030. Consequently, we have identified these four scenarios as potential alternatives and will evaluate them using the TOPSIS method.

The results of the evaluation obtained through TOPSIS are presented in Table 7. The optimal timing for introducing CEA auctions is observed in Scenario 3. In this scenario, Beijing enters Phase II in 2022 with a 10% auction allocation, followed by Phase III in 2024, where the auction proportion increases to 50%. Finally, in 2030, Phase IV is reached, achieving full CEA auctions. This scenario suggests that early implementation of CEA auctions in Beijing is favorable due to its robust economic base and potential for emissions reduction. Introducing some political regulatory pressure can effectively curtail carbon emissions while mitigating adverse economic effects.

Table 5 Policy simulation scenarios

Variables	Scenarios	Policy scenarios				
		Carbon price	Reduction rate of total CEA	RPS		
				Ningxia	Beijing	Zhejiang
Baseline scenario	BAU	62.1	0	20%	15%	7.5%
Carbon price	A1	49.68	0	20%	15%	7.5%
	A2	55.89	0	20%	15%	7.5%
	A3	68.31	0	20%	15%	7.5%
	A4	74.52	0	20%	15%	7.5%
Reduction rate of total CEAs	B1	62.1	1%	20%	15%	7.5%
	B2	62.1	2%	20%	15%	7.5%
	B3	62.1	3%	20%	15%	7.5%
RPS	C1	62.1	0	25%	20%	12.5%
	C2	62.1	0	30%	25%	17.5%

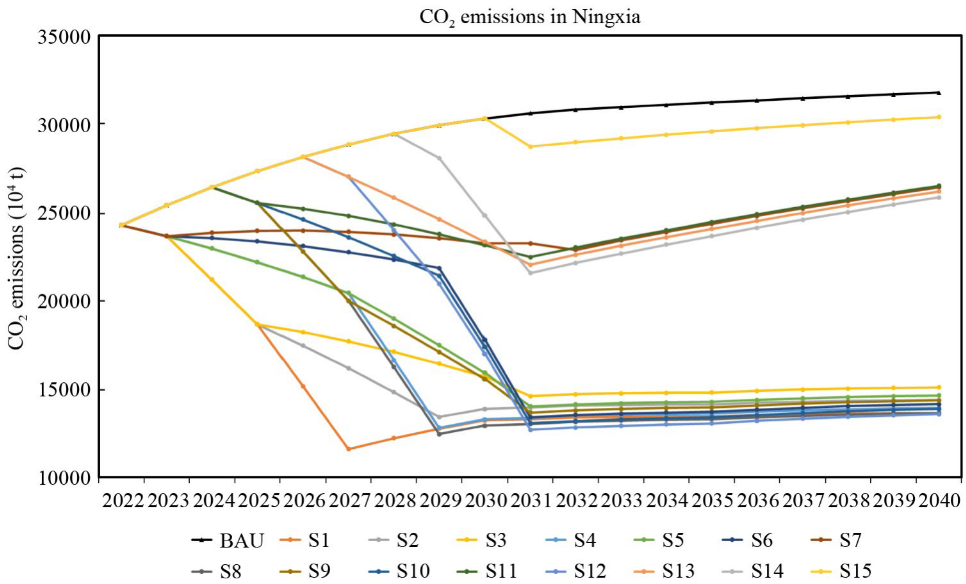

Fig. 6 The trend of CO_2 emissions under different scenarios.

Table 6 TOPSIS evaluation results

Scenario	CO_2 emissions	GDP	d_i^+	d_i^-	C_i	Rank
1	0	1	1	1	0.5	9
2	0.128658	0.872326	0.880646	0.881763	0.500317	8
3	0.26597	0.735746	0.780148	0.782344	0.500703	6
4	0.348192	0.653806	0.73804	0.740743	0.500914	4
5	0.488277	0.513928	0.705781	0.708898	0.501102	1
6	0.723717	0.278053	0.773007	0.775293	0.500738	5
8	0.481033	0.52117	0.706119	0.709233	0.501100	2
9	0.619815	0.382269	0.72535	0.728217	0.500986	3
10	0.856512	0.144578	0.867373	0.868629	0.500362	7
11	1	0	1	1	0.5	9

Figure 9 illustrates the trends in CO_2 emissions, GDP, and carbon trading volumes in Scenario 3. Implementing CEA auctions in this scenario leads to a notable reduction in CO_2 emissions, successfully achieving carbon peaking in the Beijing region. However, this is accompanied by a slowdown in GDP growth. Nevertheless, carbon trading volumes are higher than those in the baseline scenario, indicating a highly active carbon trading market.

5.1.3 Simulation results of Zhejiang

Figure 10 illustrates the trends in CO_2 emissions and GDP growth in Zhejiang across the 15 scenarios. Based on the results shown in Fig. 17, where none of the scenarios lead to Zhejiang achieving its carbon peak before 2030, the selection criterion is to reduce carbon emissions significantly while maintaining economic development as much as possible.

Next, the scenarios were evaluated by the TOPSIS method. The evaluation results are shown in Table 8.

The optimal timing is represented by Scenario 12, where the implementation of CEA auctions begins in Phase II in 2026 with a 10% auction proportion, followed by Phase III in 2028 with an increase in the auction proportion to 50%, and ultimately Phase IV in 2030 when the full CEA auctions are realized. Zhejiang, with its developed economy and significant electricity demand, faces challenges in both carbon emission reduction and economic development. The analysis suggests that delaying the implementation of CEA auctions in this region has a lesser effect on the economy. Furthermore, when 100% of the CEAs are auctioned, it effectively restrains the growth in CO_2 emissions, even if the carbon peak is not achieved. Hence, optimal Scenario 12 involves a delayed introduction of carbon allocation auctions while still transitioning to Phase IV. While this scenario may not lead to Zhejiang reaching its CO_2 emission peak by 2030, it does effectively limit emissions and fosters a more active carbon trading market. Figure 11 provides a comparative view of Scenario 12 with the baseline scenario.

The optimal scenario varies across regions due to regional heterogeneity. For Ningxia, a medium-term implementation of a carbon quota auction is advisable, while Beijing should implement it as early as possible. Zhejiang, on the other hand, should consider a later implementation. Nevertheless, the combined simulation results suggest that when the government allocates CEAs to every carbon reduction entity, irrespective of regional disparities, a complete transition to CEA auctions is crucial by 2030. This transition is a crucial measure to work toward achieving a carbon peak.

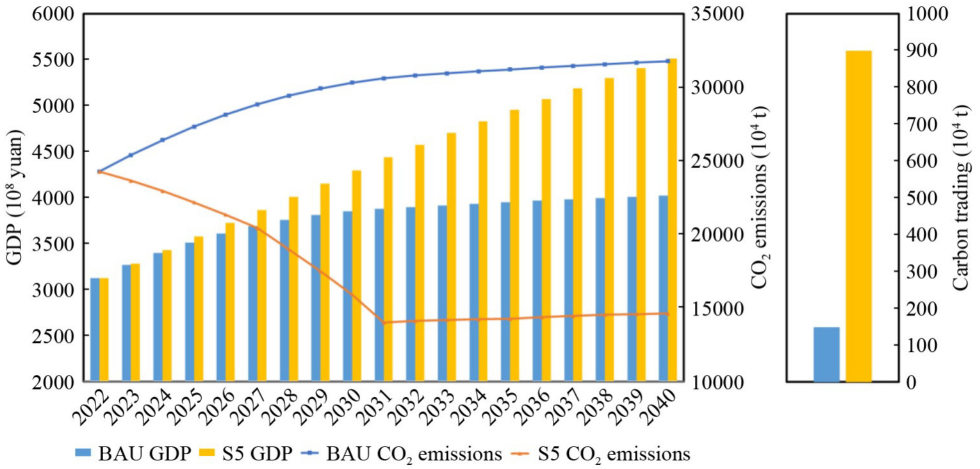

Fig. 7 CO_2 emissions, GDP, and carbon trading of BAU and S5.

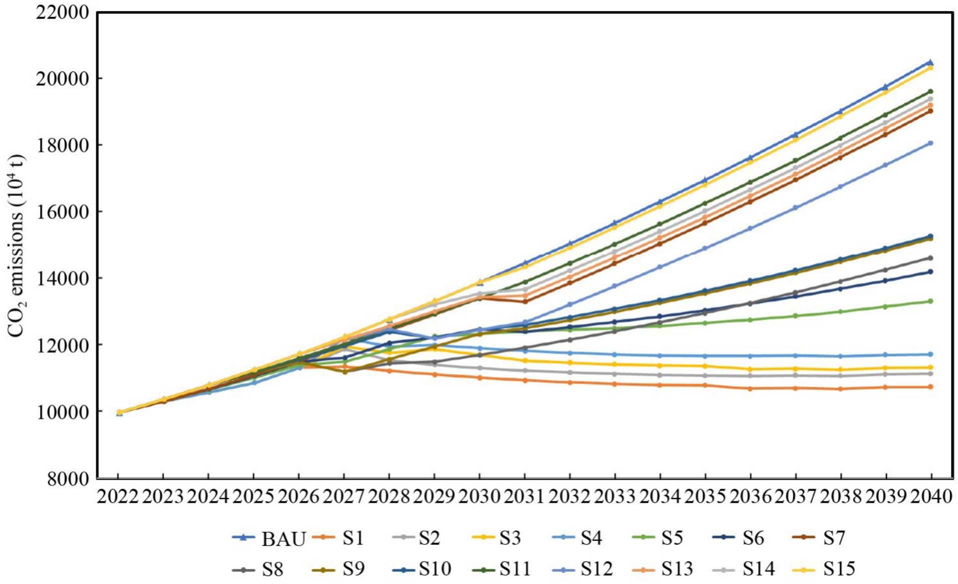

Fig. 8 CO_2 emissions in Beijing.

Table 7 TOPSIS evaluation results

Scenario	CO_2 emissions	GDP	d_i^+	d_i^-	C_i	Rank
1	0	1	1	1	0.5	3
2	0.368863	0.63114	0.731021	0.731025	0.500001	2
3	0.767393	0.232631	0.801849	0.801878	0.500009	1
4	1	0	1	1	0.5	3

5.2 Scenario analysis of carbon auction prices

5.2.1 Carbon auction price fluctuations in Ningxia

The simulation results for the four carbon auction price scenarios, labeled A1 to A4 (with carbon prices of 49.68, 55.89, 68.31, and 74.52, respectively), were analyzed using the previously mentioned methodology. The findings indicate that the carbon auction price has no effect on the decision regarding the timing of each stage of CEA auctions in Ningxia. Scenario 5 continues to be the optimal choice across all five carbon auction price scenarios. While changes in the carbon auction price do influence the effectiveness of policy implementation, they do not affect the timing. Figure 12 illustrates that as the carbon auction price decreases by 20% or 10%, or increases by 10% or 20%, CO_2 emissions decrease with higher carbon auction prices. This occurs because when all or most of the carbon quotas are allocated for free, the carbon emission cost, reflected in the auction price, is not passed on to the market.

5.2.2 Carbon auction price fluctuations in Beijing

Simulating and predicting carbon emissions in Beijing with carbon auction price variations of −20%, −10%,

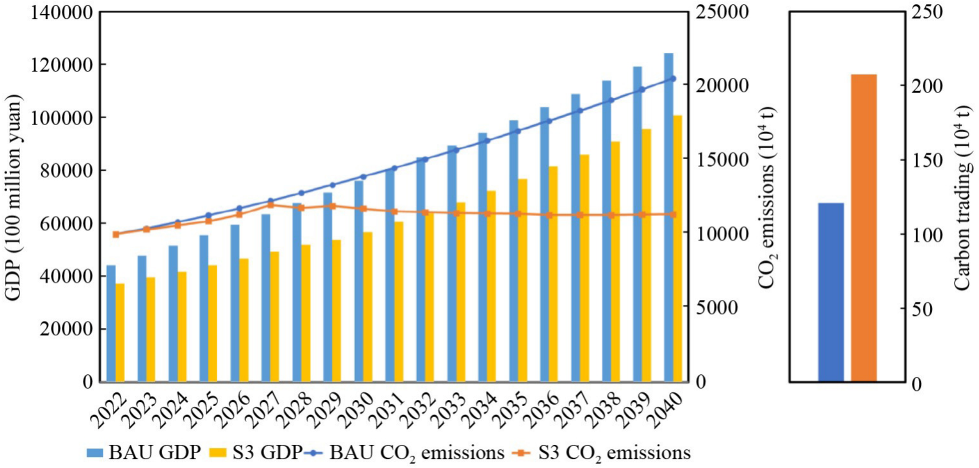

Fig. 9 CO$_2$ emissions, GDP, and carbon trading of BAU and S3.

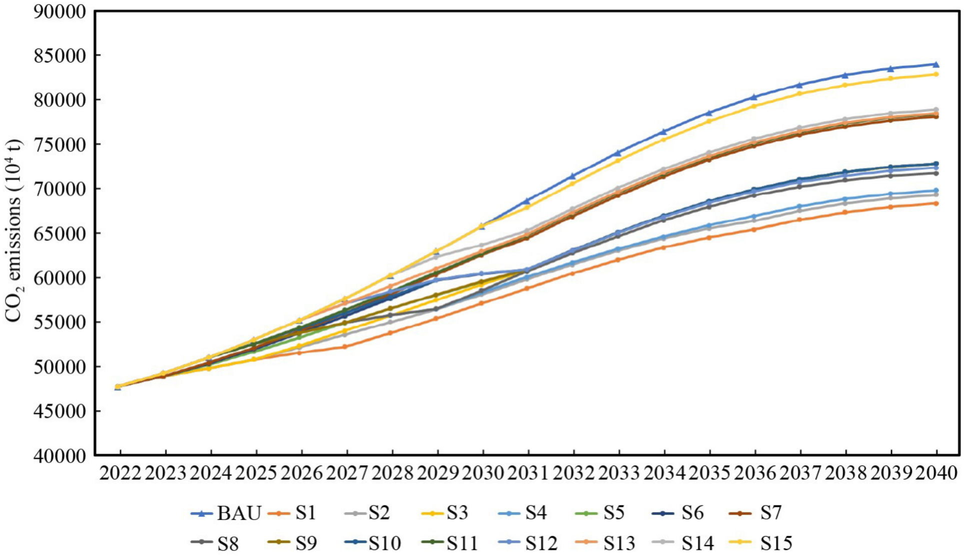

Fig. 10 CO$_2$ emissions in Zhejiang.

+10%, and +20% reveals results similar to those in Ningxia, as depicted in Fig. 13. The carbon auction price does not impact the optimal timing for introducing CEA auctions in Beijing. Instead, it primarily affects the effectiveness of the carbon reduction policy, with changes in carbon auction prices leading to corresponding shifts in policy results.

5.2.3 Carbon auction price fluctuations in Zhejiang

Simulating future carbon emissions in Zhejiang while considering changes in carbon auction prices of −20%, −10%, +10%, and +20% reveals that carbon auction prices do not impact the optimal timing for the implementation of CEA auctions. As illustrated in Fig. 14, an increase in the carbon auction price becomes crucial in reducing CO$_2$ emissions immediately after the introduction of CEA auctions. Specifically, when the carbon auction price is raised by 10% and 20%, Zhejiang attains its carbon emission peak in 2026 and 2028, respectively.

In summary, fluctuations in carbon auction prices influence policy results but do not impact the determinations of the optimal timing and allocation proportion for CEA auctions. Consequently, the auction price should not be the primary policy element when crafting the policy. Nonetheless, it is worth noting that the carbon auction price does exert a substantial influence on carbon emission reductions following the implementation of CEA auctions. A higher percentage of auctioned allocations is correlated with a more pronounced effect, underscoring the role of CEA auctions as a significant means of conveying the carbon auction price signal.

Table 8 TOPSIS evaluation results

Scenario	CO_2 emissions	GDP	d_i^+	d_i^-	C_i	Rank
1	1	0	1	1	0.5	14
2	0.999786	0.04814	0.95186	1.000945	0.512568	13
3	0.999592	0.092151	0.907849	1.00383	0.525104	11
4	0.999379	0.140472	0.859528	1.009203	0.540047	10
5	0.999195	0.182441	0.81756	1.015715	0.554044	8
6	0.998837	0.264775	0.735226	1.033335	0.58428	4
7	0.444536	0.583171	0.694468	0.733281	0.513592	12
8	0.999079	0.209097	0.790903	1.020726	0.56343	7
9	0.998897	0.251031	0.74897	1.029957	0.578976	5
10	0.998549	0.331478	0.668524	1.05213	0.611471	2
11	0.444221	0.648209	0.657759	0.785816	0.544354	9
12	0.998292	0.391342	0.608661	1.072257	0.6379	1
13	0.443941	0.706447	0.628788	0.834357	0.570249	6
14	0.443692	0.75856	0.606442	0.878792	0.591686	3
15	0	1	1	1	0.5	14

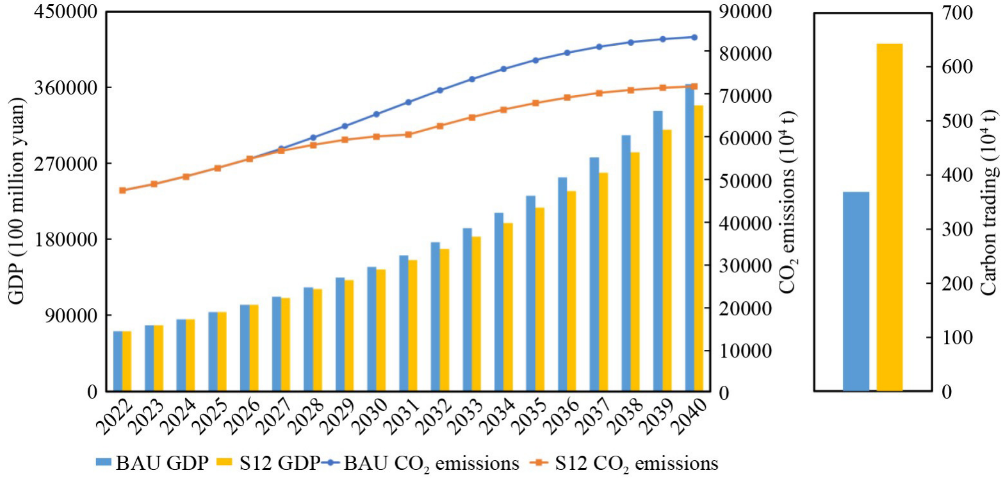

Fig. 11 CO_2 emissions, GDP, and carbon trading of BAU and S12.

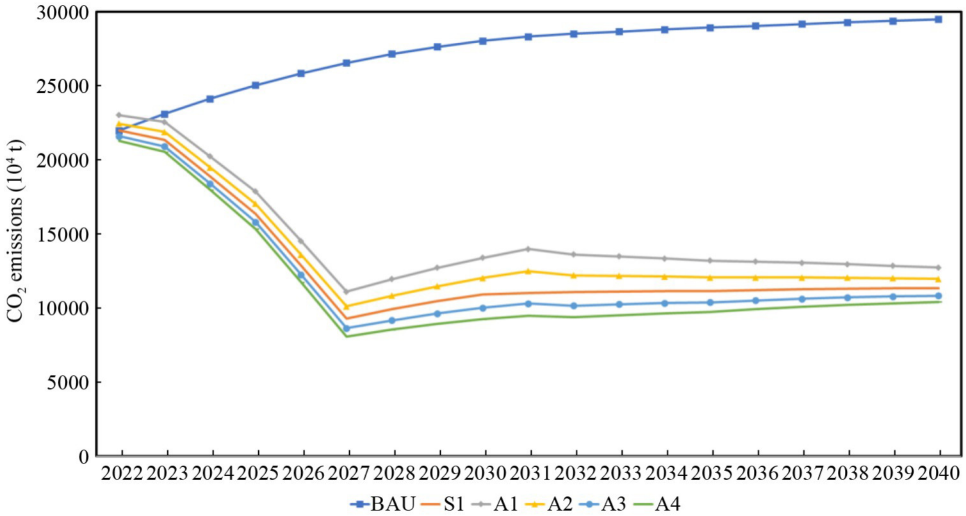

Fig. 12 CO_2 emissions in Ningxia.

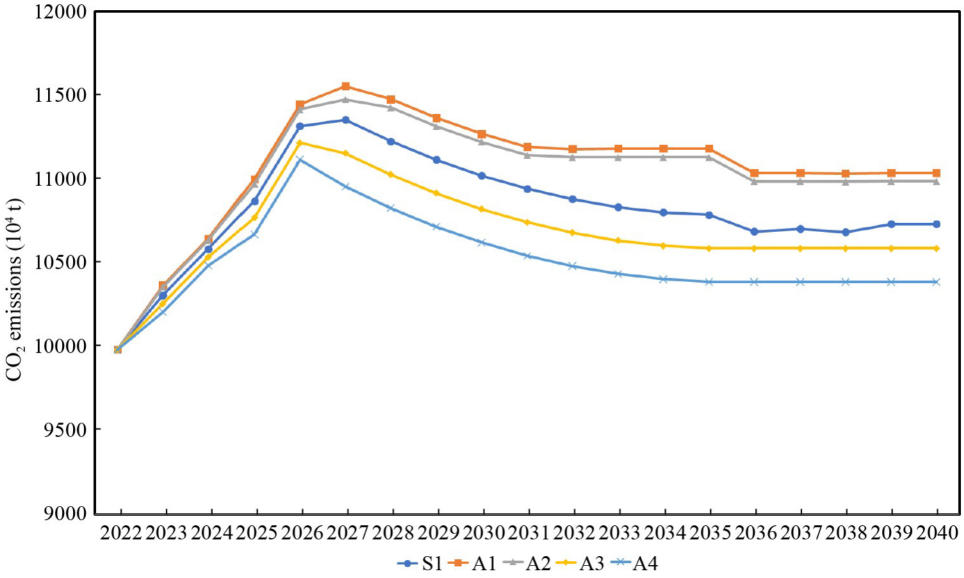

Fig. 13 CO_2 emissions in Beijing.

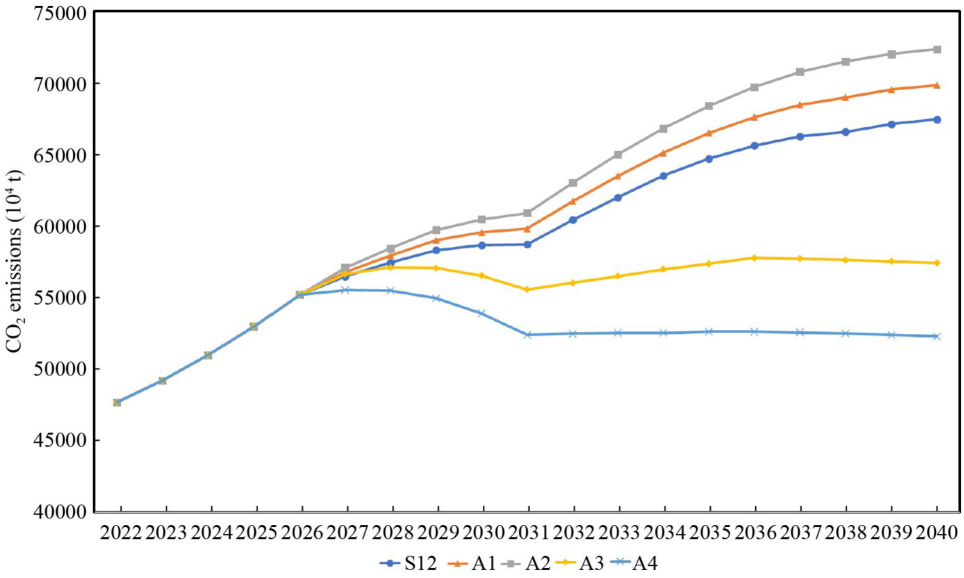

Fig. 14 CO_2 emissions in Zhejiang.

5.3 Scenario analysis of changes in total carbon allowances

5.3.1 Total carbon allowances in Ningxia

When the total quantity of CEAs issued to Ningxia decreases at rates of 1%, 2%, and 3% annually, the optimal scenarios are Scenario 4, 3, and 3, respectively. This implies that a more rapid reduction in the total quantity of CEAs is linked to an earlier optimal timing for the implementation of CEA auctions. Figure 15 illustrates the simulation results for GDP and CO_2 emissions for these optimal scenarios with varying total CEA amounts. Figure 7 reveals that as the quantity of CEAs is reduced, there is a corresponding decline in CO_2 emissions in Ningxia. Moreover, this process leads to an increase in GDP, rather than negatively impacting Ningxia's economy. This reduction in total CEAs compels power companies to reduce emissions by shifting toward renewable energy generation. Ningxia, being rich in renewable energy resources, possesses significant potential for renewable energy generation, which reduces the costs of carbon emissions. Additionally, it allows for the sale of surplus clean electricity exceeding RPS requirements through the TGC market to other provinces lacking in resources. Figure 16 demonstrates that Ningxia experiences a significant rise in renewable energy consumption, accompanied by substantial increases in the volume of

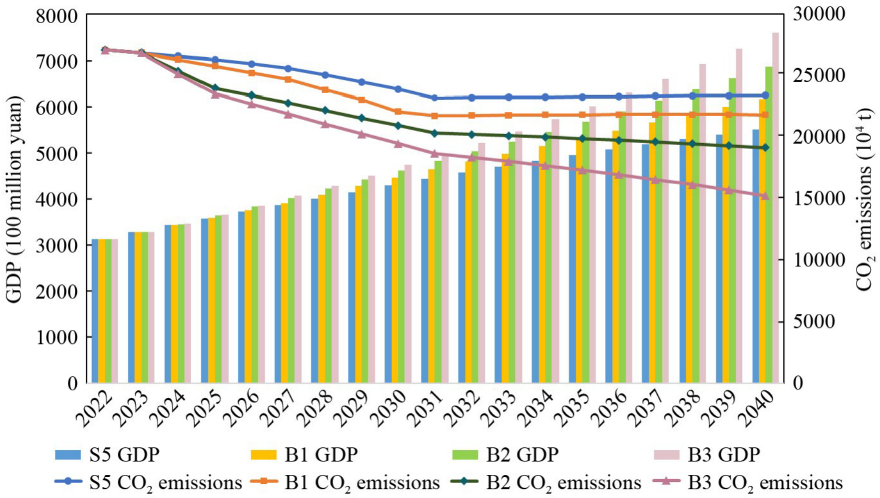

Fig. 15 CO$_2$ emissions and GDP of S5 and B1–B3 in Ningxia.

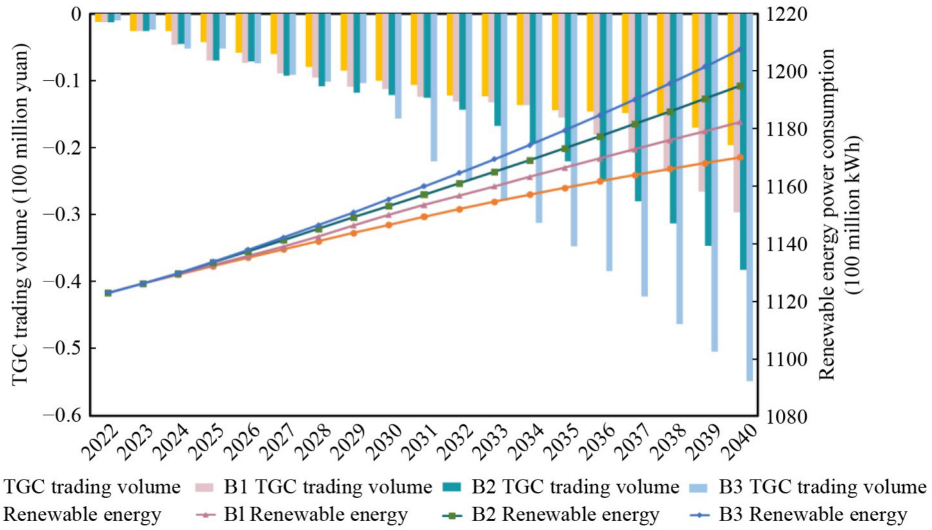

Fig. 16 TGC trading volume and renewable energy power consumption of S5 and B1–B3 in Ningxia.

TGCs sold. Consequently, Ningxia achieves higher economic benefits through the TGC market, contributing to its long-term economic development.

5.3.2 Total carbon allowances in Beijing

Figure 17 illustrates that as the total quantity of CEAs decreases at rates of 1%, 2%, and 3%, the optimal scenarios are Scenarios 6, 10, and 12, respectively. The delay in the optimal timing for implementing CEA auctions results from the tightening of CEAs policies, which leads to a reduction in the allocation of free CEAs to enterprises. This reduction compels enterprises to take measures to reduce emissions in order to avoid administrative penalties, which would otherwise increase emission costs. In response, companies make efforts to mitigate carbon emissions. However, to offset the abatement costs stemming from the reduction in CEAs, delaying the implementation of the auctions provides a sound economic foundation for subsequent carbon abatement efforts, delivering long-term economic and environmental benefits.

As the total CEAs decrease, CO$_2$ emissions gradually decline. The delay in CEA auctions offers enterprises some leeway, but they ultimately bear increased expenses to curtail emissions, leading to a reduction in GDP. Nevertheless, Beijing possesses certain renewable energy resources, enabling companies to transition more easily to renewable energy generation and partially mitigate the economic consequences.

5.3.3 Total carbon allowances in Zhejiang

Figure 18 illustrates that the optimal timing for the implementation of auctions remains consistent, as represented

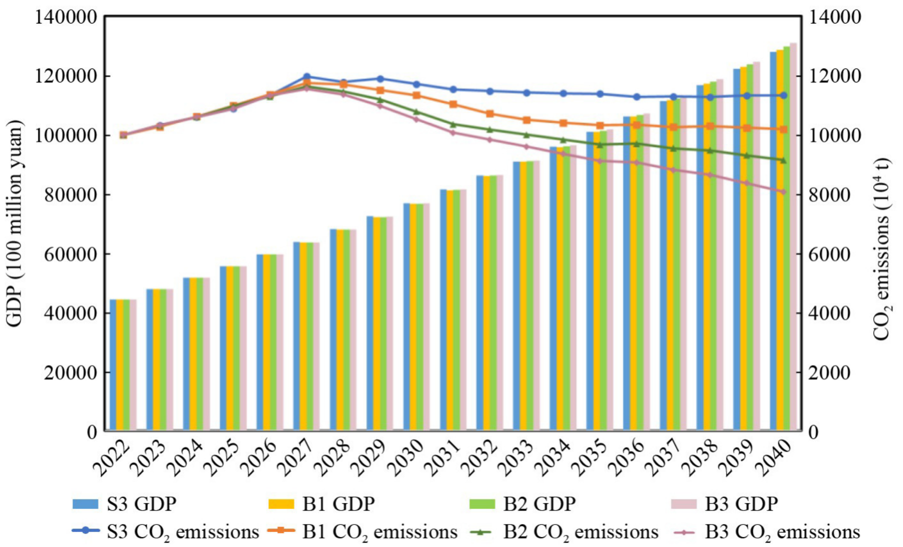

Fig. 17 CO$_2$ emissions and GDP of S3 and B1–B3 in Beijing.

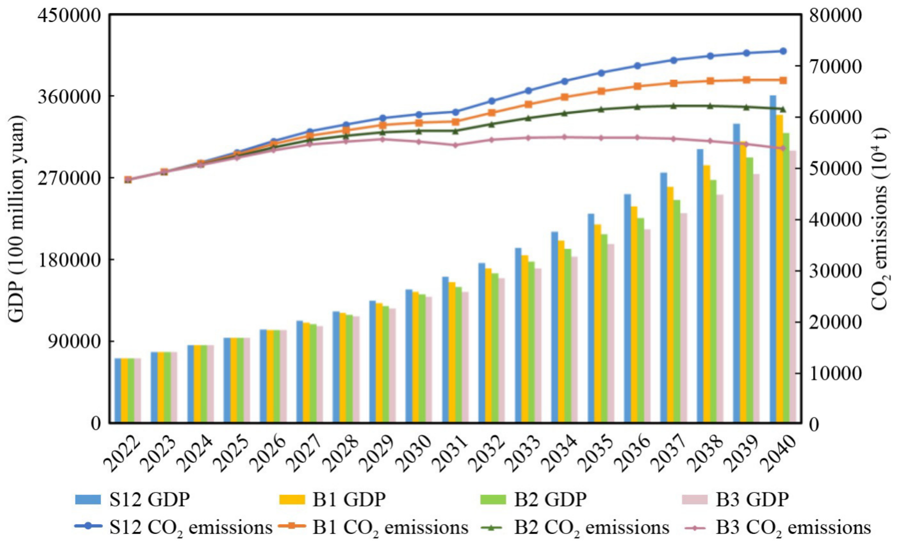

Fig. 18 CO$_2$ emissions and GDP of S12 and B1–B3 in Zhejiang.

by Scenario 12, even when the total CEA allocation decreases at rates of 1%, 2%, and 5% per year. As previously discussed in Section 3.2.3, the tightening of emission reduction policies typically delays the optimal implementation time, with Scenario 12 being the latest among the acceptable scenarios. The reduction in the total quantity of CEAs compels companies to actively reduce their carbon emissions, which experience a significant decline. Specifically, in Scenario B3, Zhejiang manages to achieve a carbon peak in 2029, albeit with accompanying reductions in GDP due to the costs associated with carbon emission abatement.

In summary, the total quantity of CEAs issued plays a pivotal role in influencing the optimal timing for the implementation of CEA auctions and their subsequent carbon reduction results. Additionally, regional spatiotemporal heterogeneity introduces varying effects, with particular emphasis on the effect of the total CEAs allocation, which could ultimately determine whether Zhejiang can attain its carbon emission peak.

5.4 Scenario analysis with different RPS increases

5.4.1 RPS changes in Ningxia

As the RPS in Ningxia increases, the optimal timing for auction implementation advances. Scenarios 4 and 3 emerge as optimal when the RPS allocation to Ningxia increases by 5% and 10%, respectively. The RPS increase compels companies to rely more on renewable energy for electricity generation, resulting in a substantial reduction in CO$_2$ emissions, as depicted in Fig. 19. However, this rise in RPS negatively impacts the economy. Figure 20 illustrates that while renewable energy generation also

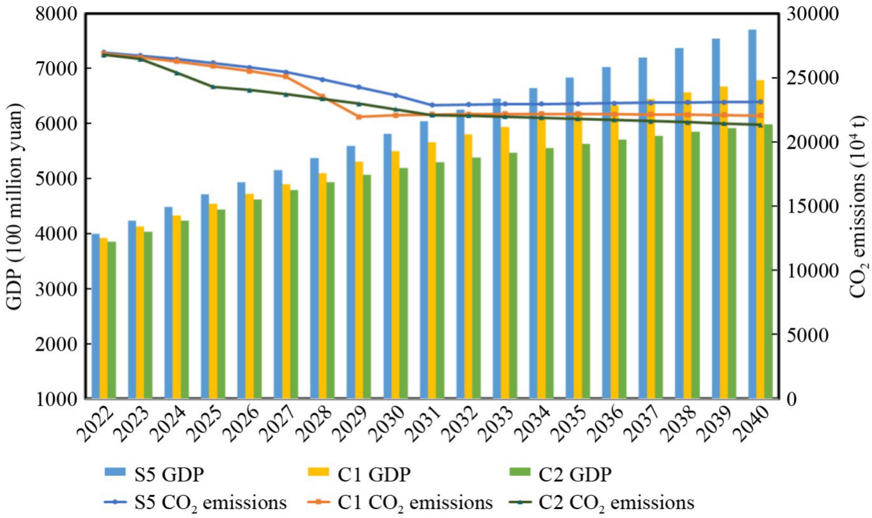

Fig. 19 CO_2 emissions and GDP of S5 and C1–C2 in Ningxia.

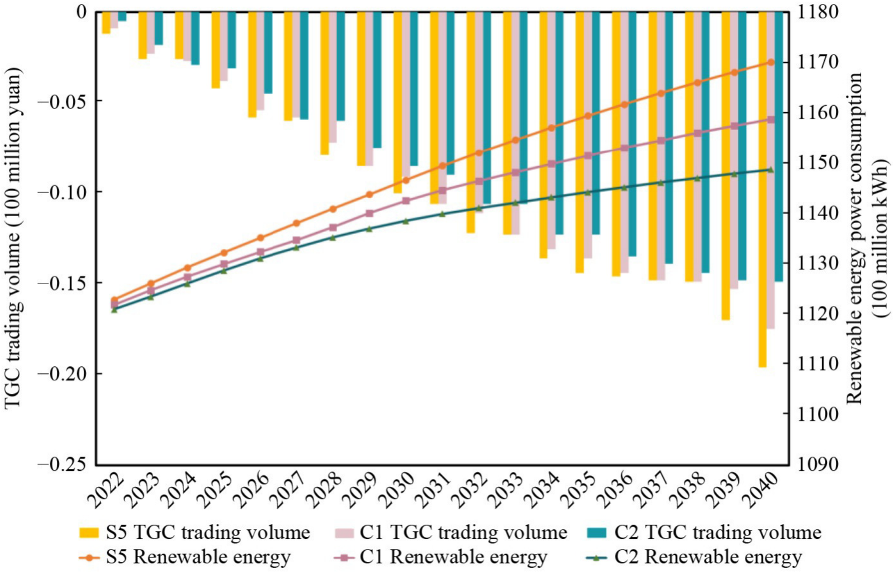

Fig. 20 TGC trading volume and renewable energy power consumption of S5 and C1–C2 in Ningxia.

increases, the heightened RPS requirement leads to a greater utilization of renewable electricity within Ningxia's RPS target. Consequently, there is less surplus TGC available for sale, causing a significant reduction in economic benefits derived from the TGC market. Hence, despite Ningxia's abundant renewable energy resources and potential for transitioning to clean electricity, the RPS target must be carefully calibrated.

5.4.2 RPS changes in Beijing

Figure 21 reveals that when Beijing's RPS increases by 5% and 10%, it has no effect on the optimal implementation timing, and Scenario 3 remains the optimal choice. The rise in RPS leads to a minor reduction in CO_2 emissions and a decrease in GDP. As the RPS escalates, the proportion of renewable electricity in the overall power source mix, illustrated in Fig. 22, also rises, resulting in increased consumption of renewable electricity and reduced CO_2 emissions. However, there is only a marginal increase in renewable energy consumption because Beijing's limited renewable energy resources cannot support a swift transition to a clean electricity source structure. Beijing must procure TGCs from other provinces to successfully meet its RPS target.

5.4.3 RPS changes in Zhejiang

Figure 23 illustrates that when Zhejiang's RPS increases by 5% and 10%, the optimal implementation plans are Scenarios 12 and 6, respectively, which accelerate the optimal timing. With the increase in Zhejiang's specified

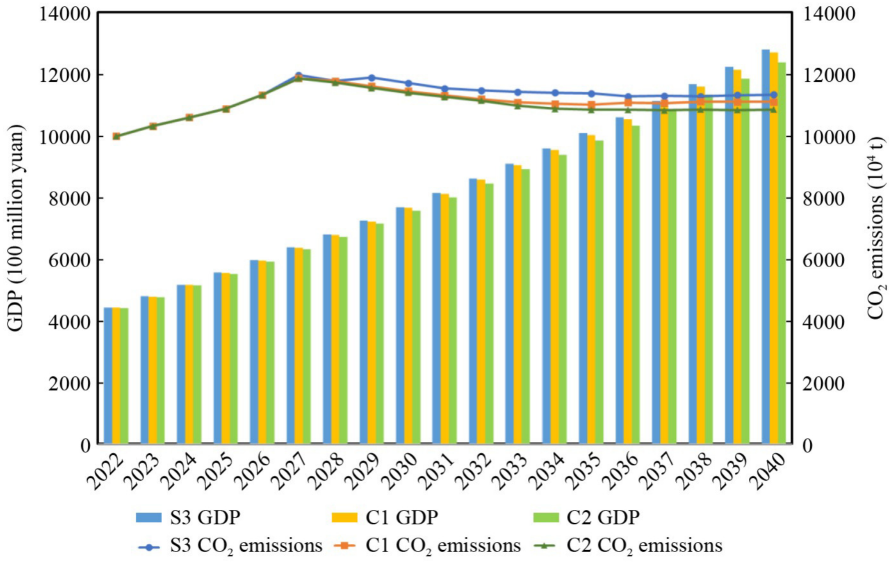

Fig. 21 CO$_2$ emissions and GDP of S3 and C1–C2 in Beijing.

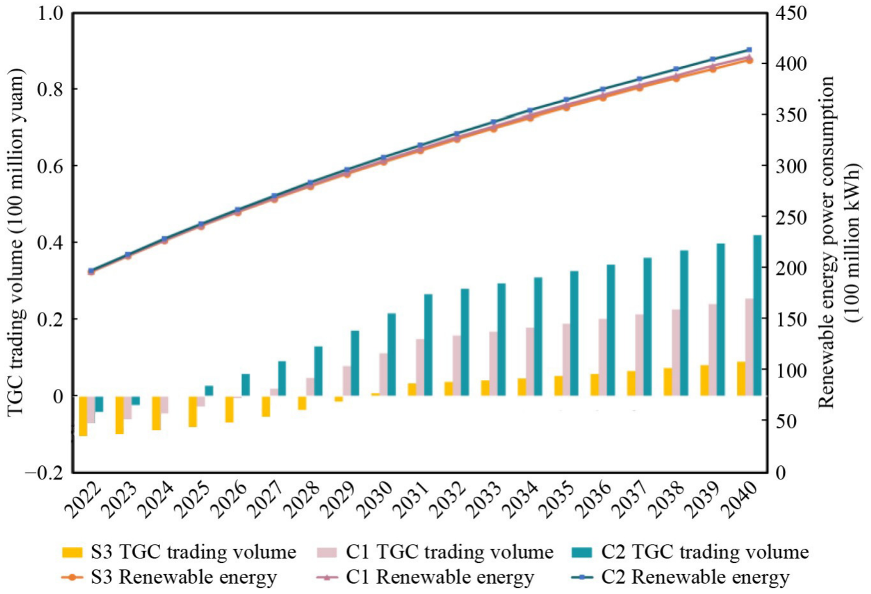

Fig. 22 TGC trading volume and renewable energy power consumption of S3 and C1–C2 in Beijing.

RPS, there is a decrease in GDP and a reduction in CO$_2$ emissions, along with a slight uptick in renewable electricity consumption. However, the growth in RPS imposes a demand for transforming Zhejiang's power source structure. Given Zhejiang's limited and costly renewable energy generation capacity, electricity companies in the region are more inclined to procure TGC allowances or clean electricity from resource-rich provinces rather than engaging extensively in renewable power development. Figure 24 reveals that Zhejiang's renewable electricity consumption experiences only modest growth, while the trading volume of TGCs rises.

In summary, the RPS standard established by the government has an influence on the optimal timing for the implementation of CEA auctions, as well as on emissions reduction and the power sector. The relationship between the RPS setting and the regional availability of renewable energy resources is not insignificant. The variation in the endowment of renewable energy resources across regions explains the diverse responses of emissions reduction and power structure enhancement to RPS modifications in the three provinces.

6 Conclusions and policy implications

This study conducted a comprehensive analysis of the factors influencing the implementation of CEA auctions

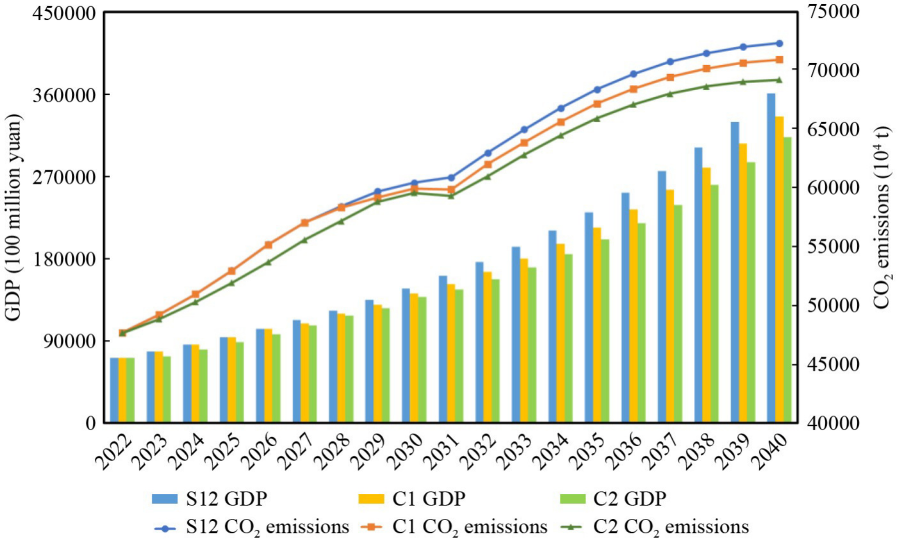

Fig. 23 CO$_2$ emissions and GDP of S12 and C1–C2 in Zhejiang.

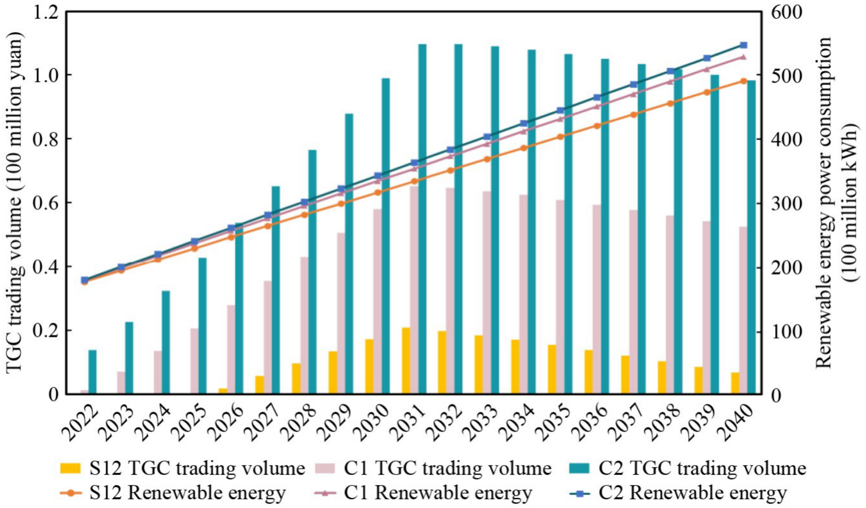

Fig. 24 TGC trading volume and renewable energy power consumption of S12 and C1–C2 in Zhejiang.

and their implications for the carbon market in China. It utilized a SD model including regional carbon emissions and a CET market with TGCs to determine the optimal timing and auction proportions in different regions. The approach considered both economic and environmental aspects, aligning with the principles of sustainable development.

The findings suggest that in Ningxia, Scenario 5, implemented in the middle of the timeframe, is the optimal choice for CEA auctions. Beijing should opt for Scenario 3 to implement auctions as soon as possible, while Zhejiang should consider Scenario 12, indicating a later implementation. In the best-case scenario, Ningxia has the potential to increase its GDP by 6.20% and reduce carbon emissions by 21.59%. This province can more easily balance environmental and economic considerations due to its abundant renewable energy resources. In contrast, Beijing and Zhejiang face greater challenges, with emission reductions of 45.15% and 13.88%, respectively, potentially costing 18.95% and 6.81% of their GDP. Despite these differences, all three provinces share the common requirement of allocating 100% of CEAs before 2030 to achieve carbon peaking.

Furthermore, this study highlights the significant influence of both the total CEAs and the RPS on the optimal timing for CEA auctions and carbon emission reduction. Regions that allocate capital for carbon reduction are more sensitive to changes in the total CEAs, with Beijing potentially postponing CEA auctions by 2–3 years in response to a decrease in total CEAs. Conversely, regions with limited renewable resources are more responsive to changes in the RPS, with Zhejiang possibly advancing the implementation time by up to 4 years if the RPS is raised. In contrast, alterations in the carbon auction price primarily affect policy results rather than the timing of implementation.

The following policy recommendations are proposed based on the study’s findings:

Early Implementation of CEA Auctions: It is crucial to implement CEA auctions and move to Phase IV before 2030. This will enable the carbon auction price to significantly influence the effectiveness of the CET market and related policies, ultimately contributing to achieving a carbon peak in China.

Tailored Policies for Regional Conditions: Policies should be customized to align with the specific conditions and needs of each region. Implementing CEA auctions for regions categorized as “low–high” should occur within a medium-range timeframe. The “medium–medium” regions should initiate CEA auctions as early as possible, while the “high–low” regions should consider implementing CEA auctions later to extend Phase I of the carbon market.

Balancing Policy Stringency: Policy stringency should be carefully balanced. While it is common to associate higher potential for carbon reduction with higher RPS and emission reduction targets, stricter policies may not always yield better results. The study suggests that a punitive CET policy could be complemented by incentive-based policies like TGCs. Allowing companies to profit from renewable energy usage in the TGC market may encourage further development of renewable energy sources.

Market Improvement: It is essential to enhance the functionality of both the CET and TGC markets. The simulation model assumes smooth and stable market transactions. To incentivize enterprises across all regions to participate in carbon emissions reduction and renewable energy investment, considerations should include matching markets and marketizing power trading. These measures can fundamentally encourage enterprises to engage in reducing carbon emissions and increasing renewable energy adoption.

While the study offers valuable theoretical insights and practical implications, it has certain limitations:

Limited Regional Representation: The study focused on three provinces, Zhejiang, Beijing, and Ningxia, to represent three economic and resource categories. However, these regions may not fully capture the characteristics of all provinces in China. Future research should consider expanding the scope to include all provinces, thus reducing the risks associated with regional particularities.

Impact on Carbon Emissions: The variations in CEA auction phases and carbon costs borne by enterprises across provinces raise concerns about potential industry transfers to regions with less stringent carbon policies. Such transfers could impact overall carbon emissions reduction efforts and should be considered in policy design and analysis.

Competing Interests The authors declare that they have no competing interests.

Nomenclature

Abbreviations	**Variables**
CET	Carbon Emissions Trading
TGC	Tradable Green Certificate
RPS	Renewable Portfolio Standard
EU	European Union
ETS	Emissions Trading System
MAC	Marginal abatement cost
CEA	Carbon Emission Allowance
MEE	Ministry of Ecology and Environment of China
NDRC	National Development and Reform Commission
NBS	National Bureau of Statistics
TCE	Tons of coal equivalent
10K-ton	Ten thousand tons
NCETN	National Carbon Emission Trading Network
GWh	Gigawatt hour
B	Billion
Parameters	
CECoef	CO_2 emission coefficient
CorrCoef	Correction coefficient
Variables	
CE	CO_2 emissions
CVol	Carbon trading volume
PSREF	Power supply reference value
REAbs	Renewable energy to be absorbed
RECsm	Renewable energy consumption
TECsm	Traditional energy consumption
TCsm	Total electricity consumption
EnvCost	Environmental cost
AbsCost	Absorption cost
CECost	Carbon emission cost
EE	Energy efficiency
CPEN	Carbon penalty
CPEN price	Carbon penalty price
TPEN price	TGC penalty price
UnQty	Unabsorbed quantity
Tvol	TGC volume

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