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Dynamic Rollout Plan of China National Carbon Emissions Trading Scheme: A CGE-Based Analysis

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Abstract: China has announced ambitious emissions reduction targets to peak CO_2 emissions by 2030 and achieve carbon neutrality before 2060. In pursuit of these objectives, the country intends to employ carbon emissions trading schemes as a key policy tool. The national Emissions Trading System (ETS) was launched in the power sector in 2021, with plans to progressively encompass additional sectors. Notably, there is a lack of studies on the dynamic expansion during operation and the entire process modeling of the carbon allowance allocation system. This paper addresses this gap by presenting a systematic modeling of the carbon allowance allocation policy. We introduce a dynamic computable general equilibrium model that captures the entirety of the ETS process, enabling us to assess the implications of various allocation mechanisms on socioeconomic outcomes and carbon emissions, with a particular focus on dynamic rollout strategies. Our findings indicate that a phased expansion strategy minimizes economic disruptions, with early expansions yielding more significant reductions in economic losses. Although a policy of free allowance allocation can diminish carbon prices and abatement costs for participating sectors, it may incur additional economic deficits. Furthermore, technological advancements and heightened electrification are expected to mitigate macroeconomic losses stemming from the carbon market. We also explore several alternative model parameters and designs for the carbon market. Our findings can provide policy recommendations on gradual expansion, auction allocation, and market stability mechanisms when further improving the national carbon market.

Keywords: mechanism design, national carbon market, sectoral coverage, CGE

1. Introduction

Research into the design and impact evaluation of carbon emissions trading schemes (ETS) is crucial, particularly in China. The specific design of these ETS significantly influences the carbon price, which in turn affects production and emission reduction decisions by enterprises. This, in turn, impacts the overall effectiveness and cost-effectiveness of emission reduction within the carbon market. International experiences indicate that alterations to the allowance allocation scheme of the EU ETS have precipitated structural fluctuations in the EU's carbon price [1]. In China, changes in carbon prices within its pilot carbon markets are closely tied to modifications in the ETS design. Consequently, this study conducts a simulation and impact assessment of the carbon allowance allocation scheme to further refine the mechanism design of China's national carbon market.

The carbon allowance allocation scheme plays an important component in the design of the ETS, which mainly includes the cap of allowance (in line with the emission control targets), sectoral coverage, allowance allocation, and the use of auction revenue [2]. Regarding cap setting, the national ETS presently lacks a defined cap constraint, and its future alignment with China's dual-carbon target remains uncertain. From the perspective of sectoral coverage, the national carbon market exclusively encompasses the power industry currently, and how the remaining seven sectors to be included (petrochemicals, chemicals, building materials, iron and steel, nonferrous metals, papermaking, and aviation) have not yet been clearly stipulated. Regarding the allocation of allowances in the national ETS, they are currently distributed at no cost. The Ministry of Ecology and Environment has indicated that paid allowances will be introduced eventually. However, the question of how to effectively implement auction allocation still needs to be addressed.

Various studies have conducted modeling and evaluation of carbon allowance allocation schemes. For the cap control, Wang et al. [3] simulated the impact of Guangdong's carbon market on emissions under two constraints. Brink et al. [4] constructed the computable general equilibrium (CGE) model to simulate the impact of the annual linear decline factor of the EU ETS cap from 1.74% to 2.52% on European economies. For the allowance allocation, many scholars have used the agent-based model (ABM), CGE model, and optimization model to analyze principles of allowance allocation and the proportion of free allowances [5–10]. Ji et al. [5] discuss the free and auction allocation of allowances in China using the CGE model as it can provide a general equilibrium perspective and find that auctions lead to lower carbon prices and higher

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GDP losses. Wei et al. [9] model firms' decision-making behaviors in ETS based on an ABM as it has strong advantages in modeling decision-making behaviors at the firm level; they suggest improving the grandfathering method of the allowance allocation. Feng et al. [10] construct an initial carbon allowance allocation model based on the Stackelberg game model due to its effectiveness in analyzing market operations to decouple the two markets during operation; their model can help reduce the deviation between the final carbon intensity and target value. For the covered sectors, Qian et al. [11] compared the effects of different sector coverage selection criteria on emissions, welfare, and carbon leakage. The results show that it would lead to more emission reductions and a moderate economic and welfare loss to include emission-intensive sectors. Mu et al. [12] evaluated the economic impact of different sectors covered by ETSs, and the results show that covering major energy-intensive industries (emissions accounting for 76.9% of the national emissions), economic loss and emissions are less. Tang et al. [13] calculated the optimal carbon price in a market that encompasses various sectors, and it was observed that the inclusion of more sectors (chemical industry, nonferrous metals, paper, ferrous metals, nonmetallic mineral products, petroleum processing, and transportation sector) in the carbon market results in a lower carbon price. Lin and Jia [14] analyzed the economic impact of incorporating different sectors after the power sector in the first stage of the national carbon market. They found that more industries in the carbon market result in a higher GDP and a lower carbon price. Wang et al. [15] discussed the different carbon market scenarios grounded in the utilization of marginal abatement cost (MAC) curves, and they proposed that the cement industry should be the subsequent sector to be evaluated. When it comes to the auction revenue of allowances, scholars mostly use CGE models to stimulate the economic impacts of the distribution of allowance revenues among residents, enterprises, and governments [16, 17].

Existing studies lack in-depth discussion on the characterization of the whole process of carbon allowance allocation policy. Aspects of carbon allowance allocation are interrelated: for example, design differences in sector coverage will affect the formulation of the cap. The lack of consideration of an important aspect may lead to the simulation results biased and not suitable for guiding practice. In addition, in the policy scenario setting, the existing studies consider the expansion of the ETS from a static perspective, without further analysis of how the carbon market expands during operation: should the sectors be included in the carbon market step by step or at once? When should more sectors be included?

Therefore, this research addresses this gap by presenting a systematic modeling of the carbon allowance allocation policy and concentrates on the dynamic optimization of China's carbon allowance allocation scheme, constructing a carbon emissions trading analysis (CETA) model that considers the entire process of the carbon allowance allocation system (cap, allocation principles, allocation methods, allocation revenue recycling). By applying this model, we aim to ascertain the optimal future allowance allocation scheme for China's ETS, taking into account the current state of the market. Additionally, we offer relevant policy recommendations to foster the further development of the national ETS. The structure of this article is as follows: The next section outlines the model, introduces the data, and discusses key parameters. Section 3 explains the scenarios, while Section 4 illustrates the results. Section 5 discusses parameter uncertainty and compares our results with other studies. Finally, Section 6 presents the conclusions of the findings and discusses their policy implications.

2. Methods

2.1. Carbon emissions trading analysis (CETA) model

Models widely used to simulate carbon emissions trading are mainly the CGE model, AMB model, and optimization model. Compared with ABM and optimization models, the CGE model has the advantage of general equilibrium analysis from a macroeconomy perspective. For example, the carbon market will affect production cost, factor input, income, and expenditure at the same time, while production cost, factor input, income, and expenditure have interactive effects. It is essential to systematically model the carbon emissions trading mechanism and its impact on the whole economic system. As a result, we try to simulate carbon emissions trading in a CGE framework.

This study expands upon the existing China energy and environmental policy analysis (CEEPA) model [18, 19] by introducing a new carbon trading module, thereby creating the CETA model. The purpose of this modification is to enable an in-depth analysis of carbon trading in China. In this model, one unit of carbon allowance means 1 ton of CO_2 (from the combustion of fossils). The carbon allowance price represents an additional cost (benefit) to buy (sell) an additional allowance; theoretically, it is the MAC of overall sectors in the carbon market [5]. ETS cost (allowance price × allowance amount) as an additional production cost adds to the energy consumption. The model structure includes a carbon trading module and other integral components of the economic model (Figure 1). In this section, we provide a detailed explanation of the carbon trading module, as well as two related modules: the production module and the income and expenditure module. We refer to Ji et al. [5] for the foreign and trade module and closure and market clearing module and, therefore, will not cover those topics again in this paper.

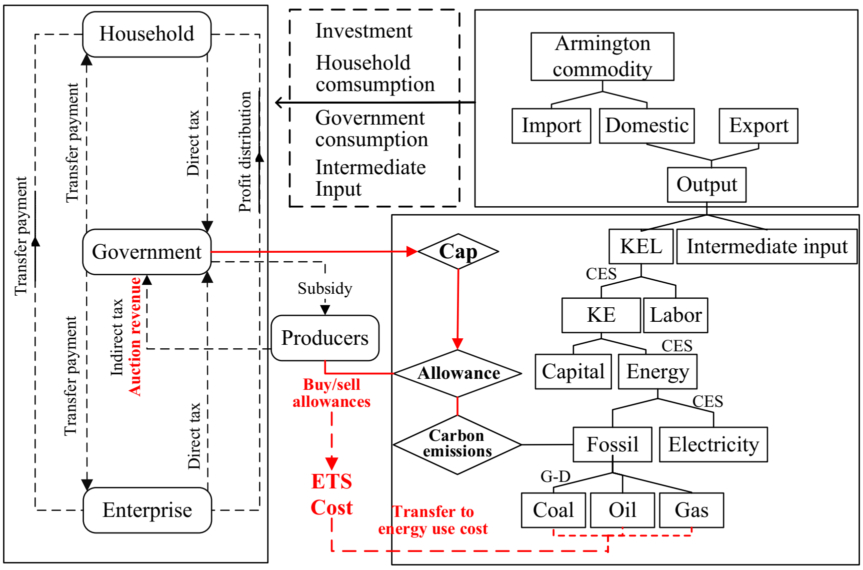
2.1.1. Carbon trading module

In the carbon trading module (red part in Figure 1), it is assumed that the carbon market is a completely competitive market, and the carbon auction price in the primary auction market is related to the carbon trading price in the secondary trading market. The allowances available to the enterprises during the compliance period include those obtained through auction or free allocation in the primary market and those traded in the secondary market. If the actual emissions of the enterprises are higher than the allowances allocated by the government in the primary market, the enterprises should purchase allowances in the secondary market to meet the compliance; otherwise, the excess allowances can be sold to obtain a profit. In particular, ETS cost includes both the cost of allowance obtained from auction and trading and the cost of allowance obtained from free allocation (which can be seen as opportunity cost). The values of free allowances return to enterprises as subsidies, so that the net cash payment of enterprises equals the actual cost of paid allowances. In such a manner, it highlights the way economic incentives are supposed to work for enterprises to reduce carbon emissions. The details of the carbon trading module in the model are as follows:

$$TOTALLO_t = \sum_{etss} ALLO_{etss,t} \tag{1}$$

$$ALLO_{etss,t} = X_{etss,t} \times CI_{etss,t-1} \times (1 - re_{etss,t}) \tag{2}$$

Figure 1
Structure of CETA model[1]



Note: The carbon trading module is in red, KEL is capital-energy-labor, KE is capital-energy KE, CES is constant elasticity of substitution function.

$TOTALLO_t$ and $ALLO_{etss,t}$ represent the total amount of allowances allocated and the sectoral amount of allowances by the government. Equation (2) means the representative principles of allowance distribution, the benchmark principle. $X_{etss,t}$ is the output of sector etss; $CI_{etss,t}$ is the initial carbon intensity of sectors covered in the ETS at year t; re is the decline rate of carbon intensity. Subscript etss represents the sector covered in the ETS.

Actual carbon emissions of different sectors are:

$$CE_{j,t} = \sum_{fec} FOF_{fec,j,t} \times PFfactor_{fec} \tag{3}$$

$CE_{j,t}$ is the actual emissions of sectors. $FOF_{fec,j}$ is the amount of fossil *fec* used by sector *j; $PFfactor_{fec}$* is the carbon dioxide emission factor of fossil *fec*.

Referring to the auction price in the existing carbon market, setting the carbon price in the primary market is related to that in the secondary market:

$$PALLO_t = \delta \times PETS_t \tag{4}$$

$PALLO_t$ is the carbon price in the primary market, $PETS_t$ is the carbon price in the secondary market, and δ is the relationship between carbon prices in the two markets. In a perfect information and perfect competition market. The two carbon prices in the two markets are equal. Therefore, the model sets δ=1.

$$QTETS_{etss,t} = CE_{etss,t} - ALLO_{etss,t} + bank_{etss,t} \tag{5}$$

$QTETS_{etss,t}$ is the amount of allowance trading. If $QTETS_{etss,t}$ is larger than 0, it indicates that the actual emissions are higher than the amount of allowance allocation; otherwise, the actual emissions are less than the amount of allowance allocation.

[1] Oil includes crude oil and refined oil; gas includes natural gas and gas. For the agricultural sector and primary energy sector, the production input includes resource input (FF) while not shown in this figure.

The model calculates $PETS_t$ through allowances trading market cleared:

$$\sum_t \sum_j QTETS_{j,t} = 0 \tag{6}$$

Additional costs of energy consumption due to ETS include all costs of obtaining allowances:

$$ETSCOST_{etss,t} = PALLO_t \times ALLO_{etss,t} + PETS_t \times QTETS_{etss,t} \tag{7}$$

$ETSCOST_{etss,t}$ is the additional cost undertaken by sectors after implementing ETS.

2.1.2. Production module

In the production module (bottom right box in Figure 1), it is assumed that each production department produces one kind of product, and production decisions are made according to the principle of profit maximization, as shown in Equations (8) and (9). In each sector, input factors include capital (K), labor (L), resource, energy (E), and non-energy intermediate inputs (M). A nested constant elasticity of substitution (CES) function is used to describe the production process. For generic economic sectors (excluding the primary energy sector and the agricultural sector), the output comprises intermediate and capital-energy-labor (KEL) input. KEL is the combination of labor and capital-energy (KE). The subsequent level is the KE bundle, made up of energy and capital. Energy includes both fossil and electricity inputs. Notably, fossil input consists of fossil fuels. For the agricultural sector and the primary energy sector, the output incorporates KELM and resource input (FF), that is, land. Given that crude oil is the most significant raw material in oil refining, and natural gas holds the same role in gas production, both are separated from the fossil fuel mix and positioned at the top tier in the production function of these two sectors. For the power sector, it considers the differences in power generation structure and uses the Leontief production function at the top to divide the power sector into two sectors, production sector and transmission and distribution sector, and then splits the power production sector into stable power generation technologies, including thermal power, hydropower, and nuclear power, and intermittent power generation technologies, including wind power and solar power generation.

$$Max\,\pi_i = PX_i \times (1 - itax_i) \times X_i - (\sum_j \alpha_{ij} \times X_i \times PQ_j + KEL_i \times PKEL_i) \quad (8)$$

$$\text{s.t.}\, X_i = LEO_i\{M_i, CES_{KEL,i}[L_i, CES_{KE,i}(K_i, CES_{E,i}(ele_i, CD_i\langle coal_i, oil_i, gas_i\rangle))]\} \quad (9)$$

where PX_i is the production cost of sector *i; $itax_j$* is production tax; X_i is the output of sector *i*; α_{ij} is the intermediate input *j* of sector *i; PQ_j* and $QINT_{i,j}$, respectively, represent the price and amount of intermediate input *j*; $PKEL_j$ and $QKEL_j$, respectively, represent the price and amount of KEL; fr_j is the free rate of allowances; and *LEO, CES, and CD,* respectively, represent the Leontief production function, *CES* production function, and Cobb–Douglas production function.

In the production module, the additional cost of ETS is mainly derived from the cost of carbon emissions via the use of fossil energy. Therefore, ETS cost is added to the cost of fossil energy use to achieve the improvement of the energy consumption structure brought by carbon costs:

$$FOF_{fec,j,t} \times (PQ_{fec,t} + \frac{ETSCOST_{j,t} \times PFfactor_{fec}}{CE_{j,t}}) = \beta_{fec,j} \times FOSSIL_{j,t} \times PFOSSIL_{j,t} \quad (10)$$

where $PFOSSIL_{j,t}$ and $QFOSSIL_{j,t}$, respectively, represent the price and amount of composited fossil fuels and $\beta_{fec,j}$ represents the share parameter of the fossil fuel *fec* in the composite fossil energy goods in sector *j*.

Allocation of allowances for free reduces the production cost of enterprises through subsidies:

$$PX_{j,t} \times QX_{j,t} \times (1 - itax_j) = \sum_i PQ_{i,t} \times QINT_{i,j,t} + PKEL_{j,t} \times QKEL_{j,t} - fr_j \times PETS_t \times ALLO_{j,t} \quad (11)$$

2.1.3. Income and expenditure module

This module (left box in Figure 1) includes government income expenditure, enterprise income expenditure, household income expenditure, and the rest of the world. Household income comprises labor earnings and profit distributions. After the deduction of household income tax and the receipt of various transfers from both governmental bodies and foreign sources, households are left with disposable income. A portion of this income is allocated toward consumption, while the remainder is saved. Enterprise income is primarily derived from capital returns. After settling enterprise income taxes and receiving government transfers, enterprises realize their post-tax net profit. This net profit is subsequently distributed as either profit sharing or retained as enterprise savings. Government revenue includes taxes and transfers from other countries or regions. Expenditures encompass government consumption, transfers to households and businesses, and export rebates. The discrepancy between government income and expenditure within a specific period represents government savings. The consumption of goods by residents and governments follows the principle of utility maximization, described by the Cobb–Douglas utility function, as shown in Equations (12) and (13). The income of the rest of the world comes from import income and the return on capital, and the expenditure includes exports, transfers to residents, transfers to governments, and savings.

$$\text{Max}: \psi_d = \prod_i (Q_{id})^{\beta_{id}} \quad (12)$$

$$st: Y_d \le \sum_i PQ_i \times Q_{id} \quad (13)$$

where *d* indicates residents or the government and β_{id} indicates the scale of expenditure. Total consumption expenditure is constrained by revenue, and Y_d implies the total income of *d*.

The way to allocate the revenues from allowance auctions in carbon trading includes being owned by the government directly, transfer payments to residents, reduction of residents' income tax, and reduction of enterprises' income tax [20]. The revenues directly returned to the government and residents can be reflected in the increased income of both parties, while the reduction in income tax for residents and enterprises can be reflected in their decreased tax expenditures. This study assumes that all the revenues are owned by the government as China's carbon emissions trading pilots do, as shown in Equation (14):

$$YG_t = TOTIITAX_t + TOTTARIFF_t - TOTEXSUB_t + TOTHTAX_t + TOTETAX_t + WtoG_t \times ER_t + ETStoG_t \times ETSREV_t \quad (14)$$

where *YG* is the income of the government; *TOTIITAX* is the indirect tax including value-added tax, consumption tax, stamp tax, and so on; *TOTTARIFF* is the tariff; *TOTEXSUB* is the subsidies including tax deductions or rebates; *TOTHTAX* is the income tax of residents; *TOTETAX* is the income tax of enterprises; *WtoG* is the transfer payments from foreign countries; and *ETSREV* is the total revenues from the ETS.

2.2. Data and parameters calibration

The primary dataset utilized in the CETA model is the 2017 input-output table, with all datasets adjusted to align with the base year of 2017. Scale parameters and share parameters are calibrated according to the social accounting matrix (SAM) 2017 made by the authors (shown in Table 1). SAM 2017 includes 41 sectors (shown in Table A1) and specifically identifies eight sectors for inclusion within the China ETS. Data of energy are from the China Energy Statistics Yearbook. Other exogenous parameters are shown in Table 2, referred to as Liang et al. [18] and Tang et al. [21].

3. Scenario Design

We set up six scenarios, including the business as usual (BAU) scenario and five other policy scenarios, as shown in Table 3.

In the baseline scenario, actual data from the National Bureau of Statistics in 2017–2021 are used to calibrate the model [22]. For future data of the baseline scenario, we refer to the Shared Socioeconomic Pathways 2 (SSP2) [23] and population data from the United Nations [24]. Total factor productivity is endogenous according to established macroeconomic assumptions.

Table 1
Social accounting matrix 2017 (100 million)

	SECTOR	LAB	CAP	FF	HOH1	HOH2	ENTE	GOV	INV	IDT	TRF	EXT
SECTOR	1440964	0	0	0	65030	256836	0	124306	366098	0	13933	150650
LAB	425170	0	0	0	0	0	0	0	0	0	0	0
CAP	299906	0	0	0	0	0	0	0	0	0	0	0
FF	6433	0	0	0	0	0	0	0	0	0	0	0
HOH1	0	63493	1693	36	0	0	16490	14943	0	0	0	–360
HOH2	0	361677	28426	610	0	0	29116	52831	0	0	0	–128
ENTE	0	0	268148	5752	0	0	0	7650	0	0	0	0
GOV	0	0	0	0	8353	57557	61974	0	0	95405	5121	–610
INV	0	0	0	0	23236	158140	173971	28069	0	0	0	–17317
IDT	95405	0	0	0	0	0	0	0	0	0	0	0
TRF	19054	0	0	0	0	0	0	0	0	0	0	0
EXT	130885	0	1639	35	0	0	0	0	0	0	0	0

Note: SECTOR: sector; LAB: labor; CAP: capital; FF: natural resource; HOH1: rural residents; HOH2: urban residents; ENTE: enterprise; INV: investment; IDT: indirect tax; TRF: tariff; EXT: the rest of the world

Table 2
Substitute elasticities[2] in CETA

Elasticities	Current value
Fossil fuels (coal, oil, natural gas, petroleum, and gas)	1
Fossil fuel and electricity input	0.5
Capital and energy	0.9
Capital-energy and labor	0.6
Intermediate inputs and KEL	0
Resource and KELM (applied to agriculture and primary energy sectors)	0.6
Electricity production and T&D	0
Stable power and intermittent power	3
Thermal power and stable clean power (hydro and nuclear)	5
Wind and solar	3
Hydro and nuclear	10
Import and domestic production (known as Armington elasticities):	
Agriculture	3
Energy products	4
Other products	2
Export and domestic sales (known as CET elasticities):	
Agriculture	4
Energy products	5
Other products	3

In the policy scenario, we constrain that carbon emissions will peak in 2030 and carbon intensity will be reduced by 65% by 2030. We set the national ETS that has been operated since 2021. The cap subject to emission reduction targets is endogenously set according to different sectoral coverage scenarios. We set three sectoral coverage scenarios to indicate different expansion speeds and selection in the national carbon market: Under the non-expansion (NE) scenario, the national ETS will not expand from 2022 to 2030. The national carbon market will expand from the power sector to all eight sectors from 2026 under the slow expansion (SE) scenario. China strives to incorporate all eight sectors into the carbon market during the 14th Five-Year Plan period, a spokesperson for the Ministry of Ecology and Environmental Protection said, in September 2020. Therefore, we set 2026 as the year for the expansion to eight sectors. The carbon market will rapidly cover the non-ferrous metals and building minerals sectors in 2023 and then cover all eight sectors in 2026 in the context of a gradual expansion (GE) scenario. This is because the government has completed the trial calculation of allowances for these two sectors. Therefore, the national ETS could cover them in 2023. In terms of allowance allocation, we set free allocation scenarios (FR) indicating all allowances free to issue based on benchmark values, referring to the "2019–2020 National Carbon Emissions Trading Allowance Setting and Allocation Implementation Plan (Power Generation Industry)." In the NE scenario, benchmark values will decrease annually by 5.5%

[2] Substitute elasticity, often referred to as cross-price elasticity of demand, measures how the quantity demanded of one good changes in response to a price change of another good.

Table 3
Scenario settings

Scenario	Sectors covered	Allocation method	Auction ratio	Revenues distribution
NE_FR	Cover the power sector only	Benchmark	0	Government
SE_FR	Expand to 8 carbon-intensity sectors from 2026	Benchmark	0	Government
GE_FR		Benchmark	0	Government
GE_FR0.5	Cover building material and non-ferrous sectors in 2023, and cover 8 emission-intensity sectors in 2026	Benchmark	0.5	Government
GE_FR0		Benchmark	1	Government

during 2021–2025 and decrease annually by 8.4% during 2026–2030. In the SE scenario, benchmark values are the same as NE's during 2021–2025 and then decrease annually by 4.9% during 2021–2025. In the GE scenario, benchmark values are the same as NE's during 2021–2025 and the same as SE's during 2026–2030. Considering the national carbon market will introduce auction allocation in the future, this study also sets two auction scenarios – 50% (FR0.5) and 100% (FR0) of allowances for auction separately, which can evaluate the impact of the auction. And revenues from the auction belong to the government, which refers to China's carbon emissions trading pilots.

4. Results

4.1. Emissions subject to Nationally Determined Contributions (NDCs) targets

To achieve the carbon peak and carbon intensity targets by 2030, fossil fuel consumptions, under five scenarios, fall by 7.86%–9.93% compared with the BAU scenario, and carbon emissions[3] decreased by a range of 8.48%–10.38%. Carbon emissions peak around 2026, peaking at about 10.4 billion tons. In the expansion scenarios, the cumulative emissions fall by 4.64% compared to BAU under the NE scenario, which is the largest reduction. The GE scenario achieves the smallest emission reductions, with a reduction of 4.06% (Figure 2). As for abatement time, the difference in the cumulative emissions reductions of the expansion scenario mainly comes from 2021 to 2025. Emission reductions in 2021–2025 under the SE scenario are fewer than other scenarios, while the highest reductions emerge under the NE scenario. From 2026 to 2030, except for the NE scenario, the carbon market expands to eight sectors, and all scenarios are subject to the same reduction targets by 2030. Therefore, the gap in emission reductions in the three expansion scenarios is narrow. During the whole period, the largest emissions abatement emerges under the NE scenario, which has not yet expanded its coverage, because sectors with lower MAC participate in the market under expansion scenarios so that economic losses are lower than un-expansion, and higher output is accompanied by higher emissions.

In the auction scenarios, the higher the auction ratio is, the greater the emission reductions are. The scenario where all allowances are issued by auction achieves a cumulative emission reduction of 5.07% compared with the BAU scenario, which is 1.01% higher than that of the free allocation scenario. Free allocation of allowances implies implicit subsidies for emission-intensive sectors; as the free ratio decreases, subsidies to emission-intensive sectors decline, stimulating emission reductions in emission-intensive sectors.

[3]Carbon emissions in this article are from the combustion of fossil fuels.

Figure 2
Changes of carbon emissions (100 million tons)

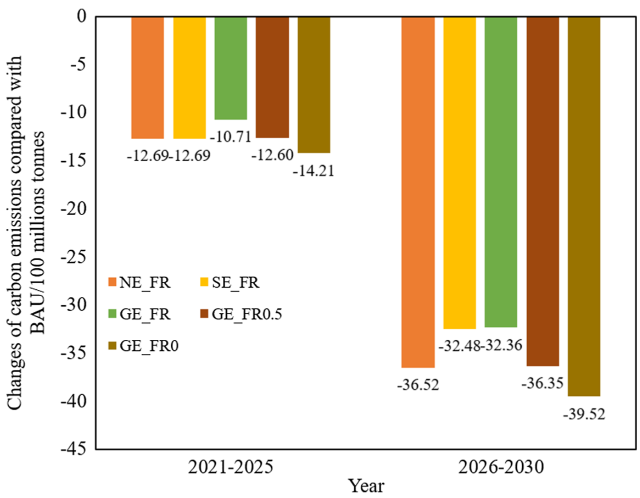
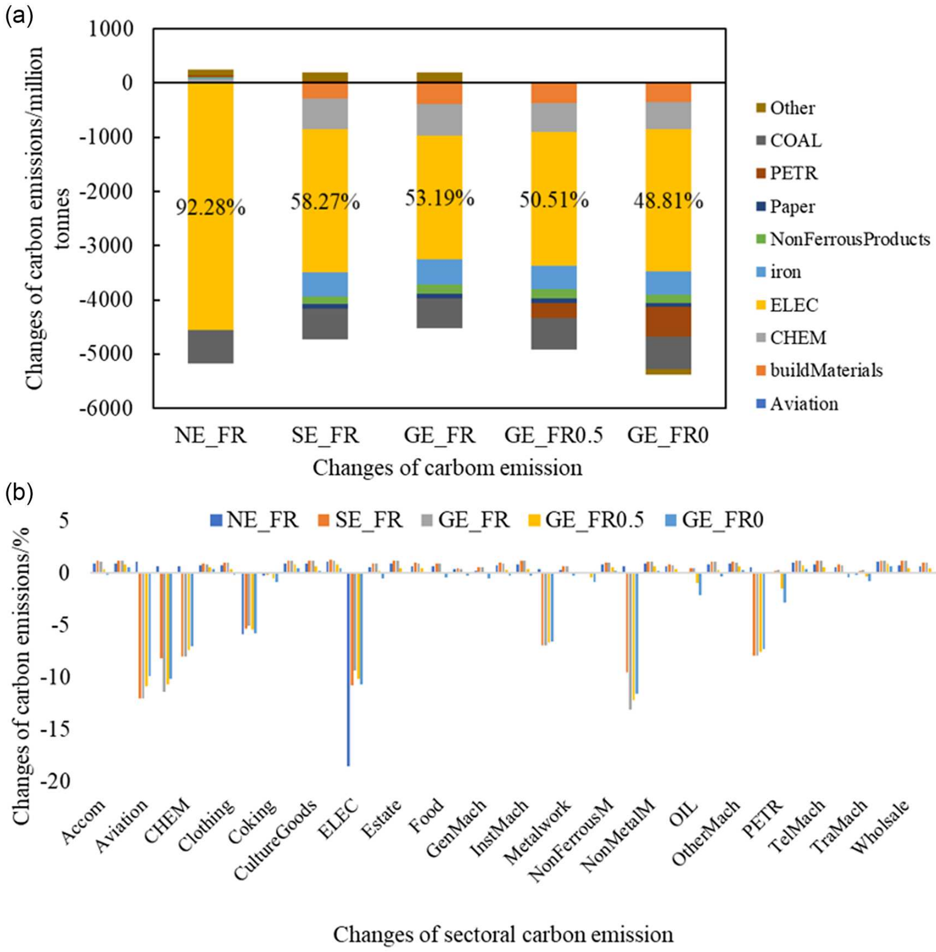


Figure 3 shows the emissions reductions of each sector under different scenarios, and the differences in emission reductions mainly result from the differences in MACs. Under all scenarios, the power sector is responsible for the most significant reductions in emissions, and the disparity in the MAC of sectors contributes to the heterogeneity observed in inter-sectoral emission abatement. The MAC associated with the power sector is notably the most diminutive [13]. Therefore, the power sector abates far more emissions than other sectors under the same carbon price level (Figure 3). Variances in the emission reductions of the power sector among the scenarios stem from different expansion options. The sooner the national ETS covers more sectors, the more sectors will contribute to emission reductions, and the faster the reduction pressure of the power market will disperse. When there is only one power sector in the market, compared with the BAU scenario, the cumulative emission reductions of the power sector account for 92.28% of the total reductions, while under the GE scenario, the ratio declines to 53.19%.

Increasing the auction ratio promotes the diffusion of emission reductions from sectors covered in the carbon market to sectors uncovered in the carbon market (Figure 3(b)). In the fully free allocation scenario (GE_FR), carbon emissions from sectors other than the energy sectors are larger than BAU, which means they are not negatively affected by the carbon market. With the increase in the auction ratio, the sectors not included in the carbon market have also been negatively affected by the carbon market policy, and their carbon emissions have started to decrease. This is because the actual production costs of the sectors covered in the carbon market do not increase as carbon prices are introduced under the fully free allocation of allowances, and the carbon costs will not be transmitted to

Figure 3
The accumulative changes of carbon emissions of sectors compared with the BAU in 2021–2030



other uncovered sectors. However, other sectors will promote production by using the production factors transferred from the covered sectors, resulting in an increase in carbon emissions. After introducing an auction in the carbon market, the actual production costs of the covered sector increase due to the increase in the cost of carbon allowances, and the cost of allowances increases as the auction ratio increases. The increase in the ex-factory price of products in the covered sector will be transmitted through the supply chain to the uncovered sectors, so that the uncovered sectors are also affected by the increase in carbon costs, leading to reduce production activities so as to reduce carbon emissions.

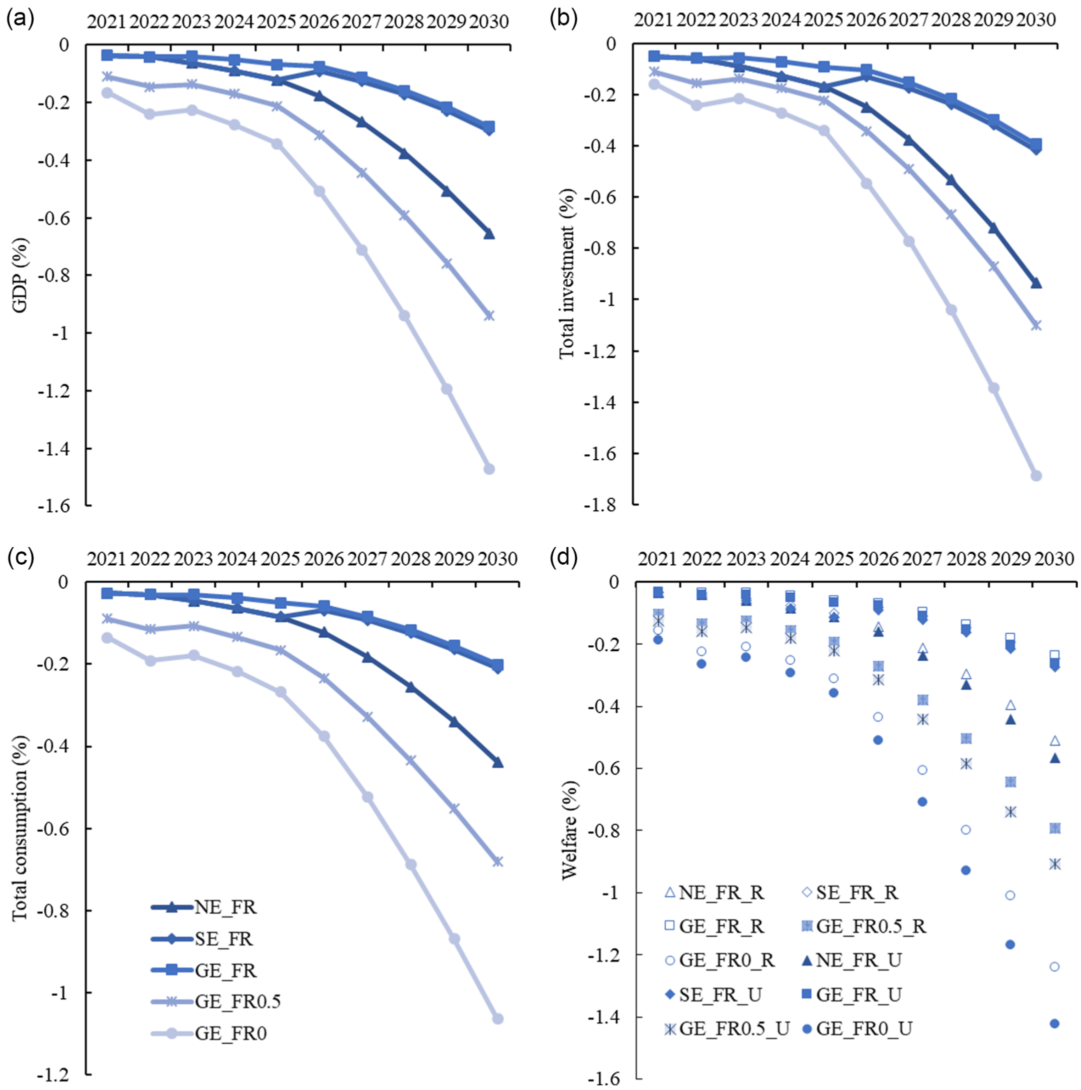
Among sectors not covered in the national carbon market, the coal production and processing sector is the sector most adversely impacted by the national ETS. Due to subject to the ETS, the demand for fossil energy declines, especially the coal with the highest level of carbon intensity. The domestic demand for coal, under the NE_FR, SE_FR, GE_FR, GE_FR0.5, and GE_FR0 scenarios, will drop by 11.94%, 11.56%, 11.54%, 11.82%, and 12.07% compared with the BAU scenario in 2030, respectively. The main consumption of coal production stems from the power sector; thus, carbon emissions of the coal sector are different under the five scenarios, mainly due to the emission constraints of the power sector under different expansion scenarios. The carbon emissions from the oil and natural gas sectors increase compared with the BAU scenario, because oil and natural gas are alternatives to coal, and the additional cost of carbon emissions from the consumption of oil and natural gas is smaller than that of coal. The accumulative carbon emissions from oil and natural gas increase by around 0.5% and 1%, respectively.

4.2. The economic impacts subject to NDCs

4.2.1. Macroeconomic impacts

The macroeconomic impacts of the implementation of the national ETS are shown in Figure 4. The economic loss of the expansion scenarios is lower than that of the non-expansion. From 2021 to 2030, the cumulative GDP loss is 0.26% under the NE scenario (Figure 4(a)), compared to a smaller loss of 0.12%–0.14% under the expansion scenario. GE, slowing the spread of carbon costs across more sectors with higher carbon abatement costs, has the best economic performance among scenarios. In addition, the economic loss is larger in the auction scenarios, ranging between 0.42% and 0.66%, and increases as the auction ratio increases. Allowance auctions increase producers' costs, and a higher auction ratio indicates a higher carbon cost. In our model, foreign savings are exogenous. Therefore, the decline in total consumption and investment leads to GDP loss. Furthermore, since government consumption is exogenous and the consumption propensity of residents is fixed, the 100% auction scenario – where GDP loss is the greatest – also results in the largest reductions in residents' disposable income and total consumption. Yet, in the GE_FR scenario, the GDP loss is the smallest, and the total consumption loss is also the smallest (Figure 4(b)). In the model, total investment depends on total savings, and the savings

Figure 4
Changes of macroeconomic performance compared with the BAU in 2021–2030



of residents and enterprises are both subject to income. Therefore, the performances of total investment and consumption are similar under the five scenarios (Figure 4(c)). Figure 4(d) shows that the national ETS has also led to the loss of residents' welfare, and the losses of urban residents are larger than those of rural residents. Due to the largest loss of residents' income and the highest increase in consumer price index[4] under the 100% auction scenario, the actual consumption loss is the largest. Under the free allocation scenarios, welfare losses are smaller than those in the auction scenarios. And both the income loss and the increase in consumer price index under the expansion scenarios are lower than those under the NE scenario, so the residents' welfare loss is slightly lower than in the NE scenario.

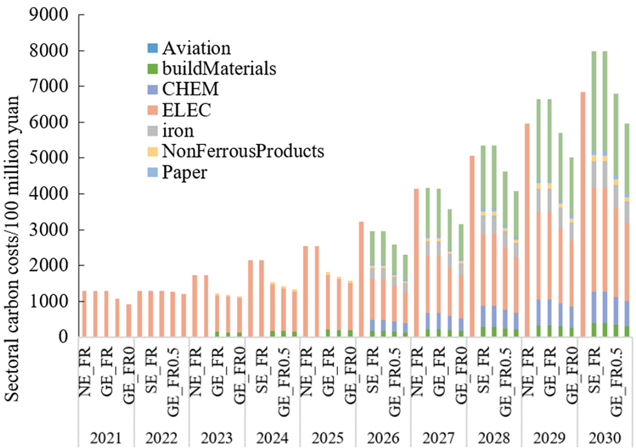
4.2.2. Carbon costs on sectors

The carbon cost in ETS is expressed as the cost of carbon emissions caused by the implementation of the policy, which includes not only the cost of carbon allowances in the primary market but also the cost of sectoral carbon allowances trading in the secondary market. The total carbon cost of trading is the sum of the costs of all sectors participating in the market. It is worth mentioning that in this study, carbon costs are implicit costs[5], while actual costs undertaken by sectors are explicit costs that are minus the subsidies from free allowances. As shown in Figure 5, first, as time goes by, the total carbon costs grow due to increasing pressure to reduce emissions. Among all sectors, the power and petroleum processing sectors exhibit the highest carbon costs, which account for more than half of the total costs. Moreover, the carbon costs of covered sectors decline due to expansion, and the sooner the market expands to more sectors, the more dispersed the cost will be. Finally, the carbon costs in the auction scenarios are lower than the others because the carbon prices and the amount of allowances in the auction scenarios are lower than the others, and carbon costs decline as auction ratios increase.

[4] Consumer price index measures the average change over time in the prices paid by consumers for a basket of goods and services.

[5] Implicit costs in this paper mean the marginal abatement cost; explicit costs are equal to implicit costs minus the subsidies from free allowances.

Figure 5
Carbon costs from 2021 to 2030



4.3. The carbon market performance

4.3.1. The carbon price

The carbon allowance price refers to the equilibrium price achieved in the trading market for allowances, where supply and demand are equal. Under these conditions, the carbon allowance price equates to the MAC of the sector participating in the market [19], which represents the cost incurred by regulated sectors for the reduction of one additional unit of CO_2. In Table 4, when the market exclusively comprises the power sector, the carbon price is 56.76 yuan/ton. By 2025, the carbon price under the NE scenario, without expansion, will be 118.89 yuan/ton, which is 1.76 times than that under the GE scenario, where the market expands to three sectors. The carbon price in the NE scenario will reach 438.05 yuan/ton by 2030, which is 3.07 times than that under other scenarios where the market has covered eight sectors. Under the NE scenario, the carbon price is significantly higher than that in the expansion scenario, and the more sectors included, the lower the carbon price is. This suggests that expanding the range of sectors within the market can effectively diminish the MAC. This is mainly due to the fact that the multi-sectoral MAC is lower than the single-sectoral MAC, and it also reminds policymakers to pay close attention to the volatility of the carbon price when covering more sectors in the national carbon market. Carbon prices decrease as the auction ratio increases. As the auction ratio increases, the discharge subsidies for the high-emission sectors will be cut, which will stimulate them to reduce emissions, so as to reduce the overall MAC of the market.

4.3.2. The trading volume in the carbon market

In the carbon market, sectors with emissions greater than the allowances issued need to purchase allowances through trading to achieve compliance, while sectors with emissions fewer than the allowances issued can sell these for profit. The market, which is similar to other sectors in the CGE model, will also be clear. As shown in Figure 6, the power sector will undertake emission reduction tasks alone, and there will be no trading under the SE and NE scenarios in 2025. In the GE scenario, the power sector is the largest buyer, while the other two sectors are sellers. It indicates that the power sector needs to purchase allowances to comply, while the building material sector and non-ferrous sector can continue to reduce emissions to obtain profits after completing abatement targets. As the power sector is the only buyer and the biggest emitter in the secondary market, this indicates that it has a great impact on the price and volume of the market. In 2030, the transactions of various sectors are similar, and the market performances are the same under the expansion scenarios. Compared with free allocation, the number of transactions in the auction scenarios is smaller than those in the free allocation scenarios. The main reason is that the number of allowances is smaller.

The trading activity, which refers to the proportion of trading volumes to the cap, usually indicates the maturity of the ETS, helpful for the market's price discovery function and the realization of the market's cost-effective abatement. Further, we calculate the proportion of inter-sectors' trading activity, Figure 6 shows that expansion can effectively increase the trading activity in the carbon market.

5. Discussions

5.1. The impacts of uncertainty of expansion time on economy

We present the economic impacts of market expansion between 2023 and 2025 (Figure 7) in this section. Whether it is a onetime expansion from the power sector to eight sectors, or the power sector takes the lead to expand to three sectors and then to eight sectors, all show the same conclusion – the earlier the expansion happens, the lower the economic loss is. China strives to include all eight carbon-intensive sectors during the 14th Five-Year Plan period. If no additional sectors are incorporated within this timeframe, the cumulative GDP loss will be at least 252.6 billion yuan greater than the expansion in 2023 to include the non-ferrous

Table 4
Carbon prices in each scenario (yuan/ton)

Year	NE_FR	SE_FR	GE_FR	GE_FR0.5	GE_FR0
2021	56.76	56.76	56.76	47.41	40.75
2022	57.21	57.21	57.21	56.98	54.76
2023	77.77	77.77	44.63	43.41	42.16
2024	98.27	98.27	56.15	52.45	49.44
2025	118.89	118.89	67.40	63.04	59.29
2026	158.29	49.52	49.38	43.16	38.68
2027	217.99	70.74	70.51	61.19	54.30
2028	283.67	92.64	92.60	80.58	71.60
2029	356.79	116.76	116.72	101.45	90.17
2030	438.05	142.82	142.77	123.72	109.85

Figure 6
Allowances trading volume under each scenario

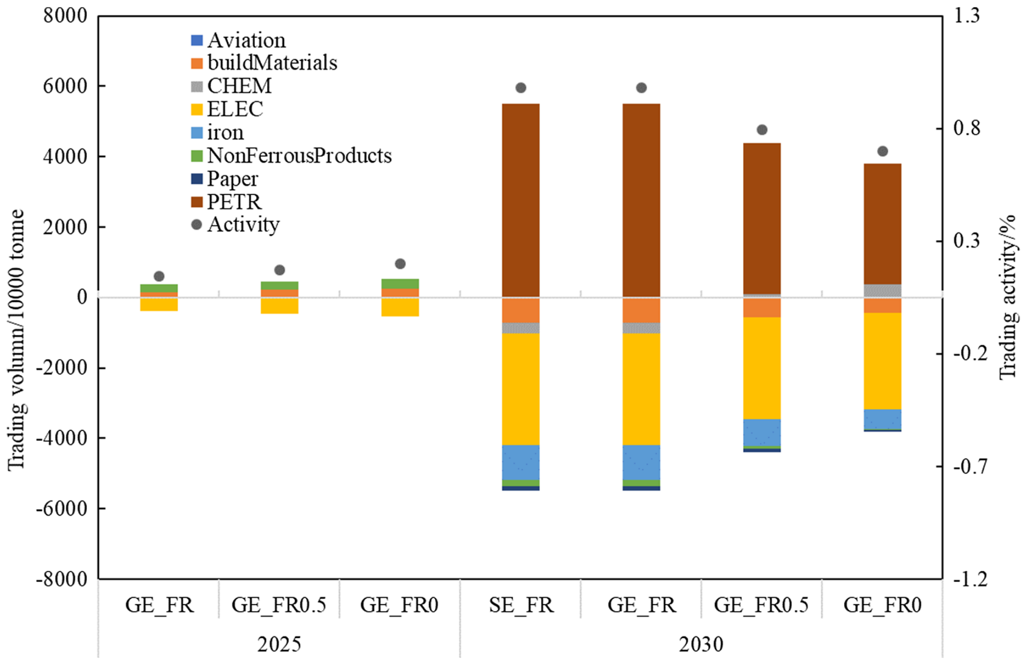
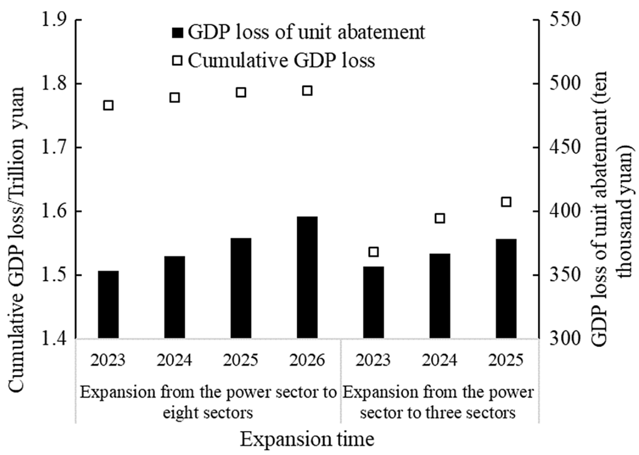


Figure 7
Cumulative emission reductions and GDP loss in different time of expansion



sector and building material sector. This implies that the GDP loss per unit of abatement (cumulative GDP loss/cumulative emission reductions) will increase by 11%. However, if the carbon market initially includes non-ferrous metals and the building material sector and then expands to cover five other sectors in 2026, the losses will be less than those resulting from a onetime expansion of all eight sectors. Therefore, it is advantageous for the national carbon market to adopt a GE strategy that prioritizes the inclusion of relatively mature sectors as soon as possible, rather than attempting to cover all sectors simultaneously.

5.2. Sensitivity analysis of substitute elasticities

Considering the limitations of the CGE model in setting elasticities, we conduct a sensitivity analysis on the key elasticities. Low-carbon technology development and energy structure improvement will have an important impact on the economy and emissions abatement costs. Therefore, we regard the substitute elasticity[6] between energy and capital and between fossil fuels and electricity as key elasticities. We discuss the of different expansion options in the market when the alternative elasticity of fossil fuels and the elasticity of energy and capital are 10% higher or lower than the baseline scenario. Table 5 shows the cumulative GDP changes and the GDP loss of unit abatement. The results imply that conclusions remain consistent under various scenarios, regardless of the substitute elasticity fluctuations. In addition, the sensitivity analysis results show that technological progress and electrification can effectively reduce GDP losses and that the impact of the changes in substitute elasticity between energy and capital on GDP is bigger. Therefore, in the future, we should pay more attention to increasing investment in low-carbon technology and energy-saving equipment to increase capital's ability to substitute fossil fuels, so as to reduce overall emission abatement costs and economic losses.

5.3. Compare with previous researches

There are currently some articles that have estimated the carbon price and economic changes to achieve emission reduction targets. The results of carbon prices in previous studies vary from scenario and settings of models. When scholars treat the cost as a production tax in the CGE model, the carbon price ranges from 365 to 9450 yuan/ton [12, 14], which is significantly higher than the results where they convert the carbon price into additional costs of energy use, which is 84–574 yuan/ton [25]. We adopt the latter, which can better reflect the effect that ETS can stimulate the substitute of energy factors. Our results show that the carbon price ranges from 110 to 438 yuan/ton under different scenarios.

[6] Substitute elasticity, often referred to as cross-price elasticity of demand, measures how the quantity demanded of one good changes in response to a price change of another good.

Table 5
Sensitive analysis of substitute elasticities

		10% reduction		10% increase	
Substitute elasticities	Scenarios	Cumulative GDP changes (%)	GDP loss of unit abatement（$ /ton）	GDP changes (%)	GDP loss of unit abatement（$ /ton）
Energy-Capital	NE_FR	–0.86	1153.01	–0.09	466.89
	SE_FR	–0.39	620.81	–0.06	338.67
	GE_FR	**–0.25**	**471.56**	**–0.06**	**319.60**
	GE_FR0.5	–0.74	1215.05	–0.24	1059.12
	GE_FR0	–1.15	1711.31	–0.39	1543.21
Fossil fuels-Electricity	NE_FR	–0.29	739.61	–0.23	636.91
	SE_FR	–0.15	418.97	–0.13	376.55
	GE_FR	**–0.13**	**376.62**	**–0.11**	**339.02**
	GE_FR0.5	–0.44	1141.89	–0.39	1083.05
	GE_FR0	–0.70	1635.29	–0.63	1581.96

6. Conclusions and Policy Implications

6.1. Conclusions

China is accelerating the construction of a national carbon market to achieve emission reduction targets. This research constructs a CEEPA-CETA model to evaluate the impacts on the economy and emissions of allowance allocation schemes in the national carbon market.

First, the results show that the earlier the expansion of the national carbon market, the lower the economic losses are. The expansion of carbon markets can facilitate the sharing of emission reduction costs among sectors. The cumulative GDP loss and emission reduction cost will be the lowest under the GE scenario (GE_FR). If the national carbon market does not expand during the 14th Five-Year Plan period (NE_FR), the cumulative GDP loss will be $ 252.6 billion higher than the GE scenario starting in 2023 (GE_FR), with the average GDP loss per ton of CO_2 emissions reduction increasing by 11%.

Second, free allowance allocation can reduce economic losses. The free allocation of allowances can reduce the actual carbon cost of covered companies, thereby reducing the overall economic loss, although the savings in economic loss are made at the expense of lower cumulative emission reduction. Compared to the scenario where all allowances are allocated for free (GE_FR), the cumulative GDP loss would increase by 0.30% and 0.54%, yet CO_2 emissions would decrease by 0.55% and 1.01% when the auction ratio increases to 50% and 100% under the GE_FR0.5 scenario and GE_FR0 scenario, respectively.

Third, the difference in the timing of expansion will lead to fluctuations in carbon prices, and expansion can effectively promote the activity of the carbon market. The expansion promotes a decrease in overall MAC and the allowances trading enthusiasm between sectors, thereby increasing the activity of the carbon market and contributing to the improvement of the price discovery function of the carbon market.

Fourth, technological advances and electrification will reduce the macroeconomic losses caused by carbon markets. The sensitivity analysis results show that a 10% increase in the substitution elasticity between capital and energy could reduce the cumulative GDP loss by 0.05%–0.27%, while a 10% increase in the substitution elasticity between electricity and fossil energy could reduce the cumulative GDP loss by 0.01%–0.03%.

6.2. Policy implications

The findings from this study's simulations offer insights into the strategic planning of the national carbon market's future advancement. (1) From the perspective of capacity expansion steps, the national carbon market has begun to verify the emissions of enterprises in all eight sectors since 2017, and on this basis, sectors that have completed allowance allocation, such as building materials and non-ferrous metals, should be covered in the carbon market as soon as possible. (2) In the early stage of the implementation of the national carbon market, the free allocation of allowances can promote enterprises' participation in the carbon market and reduce overall economic losses. As the demand for emission reduction increases after carbon peaking, the introduction of an auction scheme for allowances can be used to encourage emission reduction. (3) Considering that sharp fluctuations in carbon prices in the short term could have a negative impact on low-carbon investment, the government needs to pay close attention to the fluctuation of carbon prices after the expansion of the carbon market to maintain the stability of carbon prices. Specifically, the government could appropriately adjust the cap and timing of allowance allocation, as well as guide enterprises to reserve allowances across periods to avoid the impacts of sharp fluctuations in carbon prices during expansion. (4) In the future, covered enterprises should pay attention to increasing investment in low-carbon equipment and energy-saving equipment and improve the ability of capital to replace energy, thus reducing the cost of emission reduction.

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Ethical Statement

This study does not contain any studies with human or animal subjects performed by any of the authors.

Conflicts of Interest

The authors declare that they have no conflicts of interest to this work.

Data Availability Statement

Data are available from the corresponding author upon reasonable request.

Author Contribution Statement

Chang-Jing Ji: Conceptualization, Methodology, Software, Formal analysis, Writing – original draft, Funding acquisition. **Xiaodan Wang:** Formal analysis, Writing – review & editing, Supervision, Project administration, Funding acquisition.

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Appendix

Table A1
Sectors and abbreviations

Sector	Abbreviation
Farming, forestry, animal husbandry, fishery, and water conservancy	AGRI
Coal mining and dressing	COAL
Petroleum extraction	OIL
Natural gas extraction	NatGAS
Ferrous metals	Ferrous
Food	Food
Textile	Textile
Clothing	Clothing
Wood	Wood
Papermaking and paper products	Paper
Petroleum processing	PETR
Coking	Coking
Chemistry	CHEM
Nonmetal minerals	NonMetal
Nonferrous metals	NonFerrous
Metal products	Metalwork
Ordinary machinery	GenMach
Transportation wquipment	TraMach
Electric equipment and machinery	EleMach
Electronic and telecommunications equipment	TelMach
Instruments, meters cultural and office machinery	InstMach
Other machinery	OtherMach
Other manufacturing industry	OtherIndu
Electric power, steam, and hot water production and supply	ELEC
Gas production and supply	GasPandS
Water	Water
Construction	CONS
Wholesale, retail trade, and catering service	Wholsale
Transport, storage, postal, and telecommunications services	Transportation
Accommodation	Accom
Real estate	Estate
Education	Educ
Health	Health
Other service	Service