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Collaborative governance effects of carbon market on GHG and air pollutants emission reduction in 3E model —— analysis based on System Dynamics

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ABSTRACT

The carbon market is regarded as one of the important means to achieve China's dual carbon target. It has ancillary effect for reducing air pollution while regulating carbon emissions since climate change and air pollution share the same origin and homology. Research on how to design the carbon market mechanism in order to maximize the synergistic effect of reducing greenhouse gas and air pollution will have a very important practical impact for China. This study conducts a theoretical analysis of the collaborative emission reduction path of China's carbon market, and constructs an Energy-Economy-Environment (3E) model of the collaborative emission reduction effect of carbon trading system based on System Dynamics. After analyzing the feedback path of the core cycle of the model and verifying its performance, three main policy factors in the carbon market are explored, and their effects under the dual objectives of emission control and economic development are comprehensively evaluated. This study suggests that the exploration of the potential of carbon market for collaborative governance should be accelerated, and ensure the orderly expansion of coverage and precise setting of limits, so as to ensure the smooth achievement of carbon reduction targets while guaranteeing the social and economic development.

1. Introduction

Since the reform and opening up, China's economy has developed rapidly. While becoming the world's second largest economy, it also becomes the world's largest carbon emitter. The associated ecological and environmental problems have become increasingly prominent. Among which, extreme weather events caused by global warming and air pollution in recent years are the most serious. In 2018, the State Council issued the Three-Year Action Plan to Win the Battle of Blue Sky. In 2021, the average PM2.5 concentration in 339 cities above prefecture level was 30 $\mu g/m^3$, down 9.1 % from previous year. Although remarkable achievements have been made in the control of air pollution in recent years, the situation is still grim. In 2021, 29.8 % of cities failed to meet the PM2.5 (Particulate

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Matter that its diameter less than or equal to 2.5 μm) standards. Meanwhile as the world's largest carbon emitter, China's carbon emissions in 2021 accounted for about 33 % of the world's total, and it has become a sensitive and significant area of global climate change. In the past 20 years, the number of deaths related to high temperature weather has increased fourfold, reaching 26,800 in 2019, and the economic loss is equivalent to the average annual national income of 1.4 million people in China.

Being the world's two most serious environmental problems, climate change and air pollution actually share homogeneous origins, both stemming from the large-scale use of fossil energy. In addition, greenhouse gases and air pollutants interact with each other in the actual process of action, and contribute to the change of atmospheric environment. Ayres and Walter explored the synergistic interactions between greenhouse gases and atmospheric pollutants [1]. Subsequently, the IPCC defined synergies in the context of climate change, suggesting that other benefits from policies to reduce greenhouse gas emissions should be explicitly included in policy development. Although the definition of synergistic benefits varies among different research, there is a general consensus that climate change response measures offer synergistic benefits in combating air pollution.

Carbon market as a mature carbon pricing tool, has been widely applied around the world. As an efficient governing measure with low cost in tackling the climate change problem, carbon market plays a significant role in the process of greenhouse gas emission reduction. A study of the carbon market mechanism and how it can be designed to maximize its efficiency in combating climate change and air pollution will make significant contribution towards China's dual carbon target. In earlier research, the synergistic effects of energy policies on the mitigation of CO_2 (carbon dioxide), SO_2 (sulphur dioxide), NO_x (nitrogen oxide), and other emissions in Shanghai were investigated [2]. Another study employed modeling techniques to assess the interdependent impacts of pollution control measures and carbon reduction strategies in the European Union (EU) across six distinct climate change policy scenarios [3]. Additionally, some scholars focused on how Europe examine the reduction of carbon emissions resulting from the control of air pollution [4]. These studies collectively indicate that carbon and pollutant management exhibit certain synergistic emission reduction effects. Furthermore, through examining the relationship between synergistic emission reduction and related control measures [5], it is demonstrated that policy interventions can influence, improve, and harness such synergistic effects to achieve sustainable economic objectives.

In recent studies, researchers estimated the costs and benefits associated with five emission reduction measures implemented in the transport sector of Guangdong, Hong Kong, and Macao. Additionally, they analyzed the correlation between the cost of implementation and the rate of emission reduction [6]. Ren et al. utilized econometric methods to analyze the synergistic emission reduction effects among 30 provincial-level administrative regions in China [7]. These studies collectively indicate the positive correlation between the management of atmospheric pollutants, CO_2 and SO_2, with significant synergistic emission reductions for SO_2 in particular. Along with the establishment of seven pilot carbon markets in China in 2013 and the official launch of the national carbon market in July 2021, some studies have explored the operational mechanism of China's pilot carbon markets based on the perspective of regional carbon markets [8], attempting to depict the specific impact of carbon markets on the 3E (Energy-Economy-Environment) system from a regional perspective. In addition, some studies have also taken a stand on the macro position of the national carbon market and quantified the emission reduction effect and the specific impact on the development of China's economy or industry brought by changes in the elements of the carbon market mechanism by building different models, with a view to further optimizing the mechanism setting of the carbon market [9].

However, there have been many studies on the mechanism setting of the carbon market or impact on GHG emission reduction, but no research on the specific effect of the carbon market on collaborative governance and the related mechanism setting. Therefore, this study attempts to explore further in order to increase the operational efficiency of the carbon market in collaborative emission reduction.

In terms of the operation of the carbon market, which is characterized by a non-linear complex system with multiple subjects, multiple objectives and multiple feedback loops, with a complex internal structure, many influencing factors and dynamic development characteristics such as high-order delays, it is challenging to analyze it effectively using traditional game theory, linear programming or other precise mathematical models. Many scholars have simulated the operation of domestic pilot carbon markets and their impacts based on System Dynamics theory, such as the synergistic operation of the carbon market-emissions market in Chongqing [10], the impact of the operation of the carbon markets in Beijing and Tianjin on the 3E system in the Beijing-Tianjin-Hebei region [11], etc. These studies generally agree that System Dynamics, as a powerful tool for analyzing and dealing with complex system issues, is suitable for carbon market simulation modelling. In this study, we propose to adopt a System Dynamics method to analyze and optimize the carbon market mechanism in terms of the synergistic management of GHG and air pollutants.

2. Methods

Feasibility of synergistic emission reduction effect of carbon market is firstly elaborated based on the common origin of climate change and air pollution which is the essential condition of the study. By sorting out the key elements in the design of carbon market mechanism, we theoretically analyze the mechanism of carbon market synergistic governance. Based on which, we outline the subsystems of the 3E model of System Dynamics and further characterize the enhancement or moderating feedback relationship of the key factors among the subsystems.

2.1. Feasibility of carbon markets to promote synergistic emissions reductions

In response to the synergistic management of GHG and air pollutants, the two main approaches currently adopted are energy efficiency improvement and energy structure transformation, and the carbon market is a powerful tool to stimulate energy efficiency improvement and clean energy structure transformation by market-based means in addition to administrative command means, and during the operation phase of the trading pilot, power, petrochemical, steel, transportation, and construction industries were included, and the operation of the trading pilot effectively reduced the carbon intensity of the region [12]. The carbon market is a type of instrument to charge high emitting industries by raising their emission costs, and through the transmission of price signals to move emissions forward from end-of-pipe treatment to pre-production control, reducing emissions at the beginning, and therefore reducing the production of air pollutants along with GHG due to the reduction in the combustion of fossil energy. It has been discovered that the operation of pilot carbon markets can also significantly reduce local air pollution concentrations and SO_2 emissions [13], proving that the use of carbon markets can simultaneously mitigate climate change and combat air pollution.

The elements of carbon market mechanism cover many aspects, including establishing its scope (industry, gas, threshold, upstream and downstream, etc.), total amount of allowances (mode, type, quantity, etc.), allowance allocation (free distribution of quota, auction, etc.), offset mechanism, storage mechanism, price regulation mechanism, and regulatory approach, Monitoring Reporting and Verification (MRV), and penalty mechanisms [14].

2.2. Analysis of the mechanism of synergistic carbon market governance

This study selects CO_2 and SO_2 as the target for synergistic treatment since carbon dioxide is a major component of GHG and sulphur dioxide is a major component of air pollution. In terms of measuring the effect of the carbon market, this study mainly considers the relative emission reduction, i.e. the quantity of sulphur dioxide that can be reduced by one unit of carbon dioxide emission reduction, which mainly depends on the structural characteristics of the emission sources regulated by the carbon market, i.e. the energy structure and process characteristics of the emission sources, etc. The scope of the industry coverage is the main factor in determining the relative emission reduction in the effect of the carbon market synergistic emission reduction. Different coverage and sequence of including industry will result in different carbon market outcomes on relative emission reductions.

System Dynamics is based on feedback regulation theory, integrated system analysis and system control, and is a simulation method that effectively combines qualitative and quantitative analysis, based on qualitative analysis, the numerical and theoretical relationships of the subsystem variables are depicted and assigned to carry out quantitative analysis.

The national carbon trading system based on the 3E model consists of three subsystems: economic, energy and environmental, each of which has a complex interaction and the elements in the subsystem are also interrelated. Examining the coupling of these subsystems from a System Dynamics perspective will not only contribute to advance the study of the structural efficiency of the carbon trading market at its root, but also provide a reference for the analysis of the efficiency of related macroeconomic policies.

2.3. System dynamics 3E model of causal loop analysis

The main variables in the economic subsystem developed in this study are the level of economic development, industrial GDP, the cost of carbon emissions, the output value of emission control industries, the investment in end-of-pipe treatment, and the price of carbon; the main variables in the energy subsystem are fossil energy consumption, energy efficiency, energy transition, and industry coverage; and the main variables in the environmental subsystem are carbon emissions and pollution, carbon trading volume, free allowances, and excess emissions. The causality diagram is the key to using System Dynamics to connect the subsystems to the actual problem, and consists of a closed-loop loop that is coupled to each other and a pendulum, where the pendulum is a factor that is outside the closed loop but connected to it. The factors in the causality diagram are connected by feedback, which consists of enhanced feedback (S) and moderating feedback (O), with enhanced feedback characterizing a positive directional correlation between the two factors and moderating feedback characterizing a positive oscillation or negative directional correlation between the two factors.

The specific cause-effect relationships for the main loops included are shown below.

(1) Industrial GDP → (O) level of economic development → (S) industry coverage → (S) output value of emission control industries → (O) carbon emissions and pollution → (O) amount of free allowances → (S) amount of carbon trading → (S) cost of carbon emissions → (O) industrial GDP.
(2) Industrial GDP → (O) Level of economic development → (S) Industry coverage → (S) Output value of emission-controlled industries → (O) Carbon emissions and pollution → (O) Excess emissions → (S) Penalty price → (S) Carbon price → (S) Cost of carbon emissions → (O) Industrial GDP.
(3) Carbon Emissions and Pollution → (O) Amount of Free Allowance → (S) Amount of Carbon Trading → (S) Cost of Carbon Emissions → (O) Industrial GDP → (O) Level of Economic Development → (S) Level of Technological Development → (S) Energy Efficiency → (O) Carbon Emissions and Pollution.
(4) Carbon emissions and pollution → (S) Cost of environmental management → (O) Level of economic development → (S) Low carbon investment → (S) Energy transition → (O) Fossil energy consumption → (O) Carbon emissions and pollution.

The carbon emissions and economic development cycles (the first three) are derived from the analysis of the relationship between industrial activities, industry coverage, and carbon emissions and pollution, as discussed by Stern [15] and Dinda [16], combined with the carbon market mechanisms in China.

The internal management cycle of enterprises (the last one) is based on the discussion by Stern et al. [17] regarding the significance of carbon investments and energy transition in reducing carbon emissions and mitigating the environmental impact of industrial activities, and it is further informed by the strategic orientations commonly adopted by Chinese companies.

3. Data and sources

3.1. Stock flow analysis of synergistic emission reduction effect in carbon market

The System Dynamics model of the synergistic effect of pollution reduction and carbon reduction in the national carbon market follows the following assumptions:

First, carbon emissions discussed in this study are limited to CO_2 emissions caused by industrial processes such as the use of fossil fuels or cement production.

Second, sulphur emissions discussed in this study are limited to SO_2 emissions caused by industrial processes such as the use of fossil fuels or blast furnace steelmaking.

Thirdly, it is assumed that the system boundary is fixed. The simulation and analysis are carried out in the system boundary determined above, while other factors outside of the boundary are not considered.

The research data of this study mainly come from China Energy Statistical Yearbook, China Environmental Statistical Yearbook, China Statistical Yearbook, IPCC National Greenhouse Gas Inventory Guide and Manual of Industrial Pollutant Generation and Emission Coefficients. The data of exogenous variables such as carbon price and auction price are derived from pilot carbon market policies and related literature.

To ensure the high fidelity of integrated 3E model as a closed-loop system, each subsystem of the carbon market actually interacts and cooperates with each other with different degrees, ultimately reaching the balance of the whole system (Fig. 1).

3.2. Model variables

The fundamental system variables are presented in Table 1.

3.3. Equation setting

In order to make the model accurately reflect the actual behavior of the system, the modeling process of this study pays attention to the actual data law and employs the following methods to deduce.

3.3.1. Mathematical calculation method

The method of mathematical calculation is mainly used to estimate the growth coefficient and growth rate, and it is widely employed in parameter estimation. In this model, cement production factor, industrial GDP growth rate and blast furnace steelmaking factor are estimated by this method. Taking the growth rate of industrial GDP as an example, it is the ratio of the difference between the current industrial GDP and the industrial GDP of the delayed period set by the model and the industrial GDP of the delayed period. The

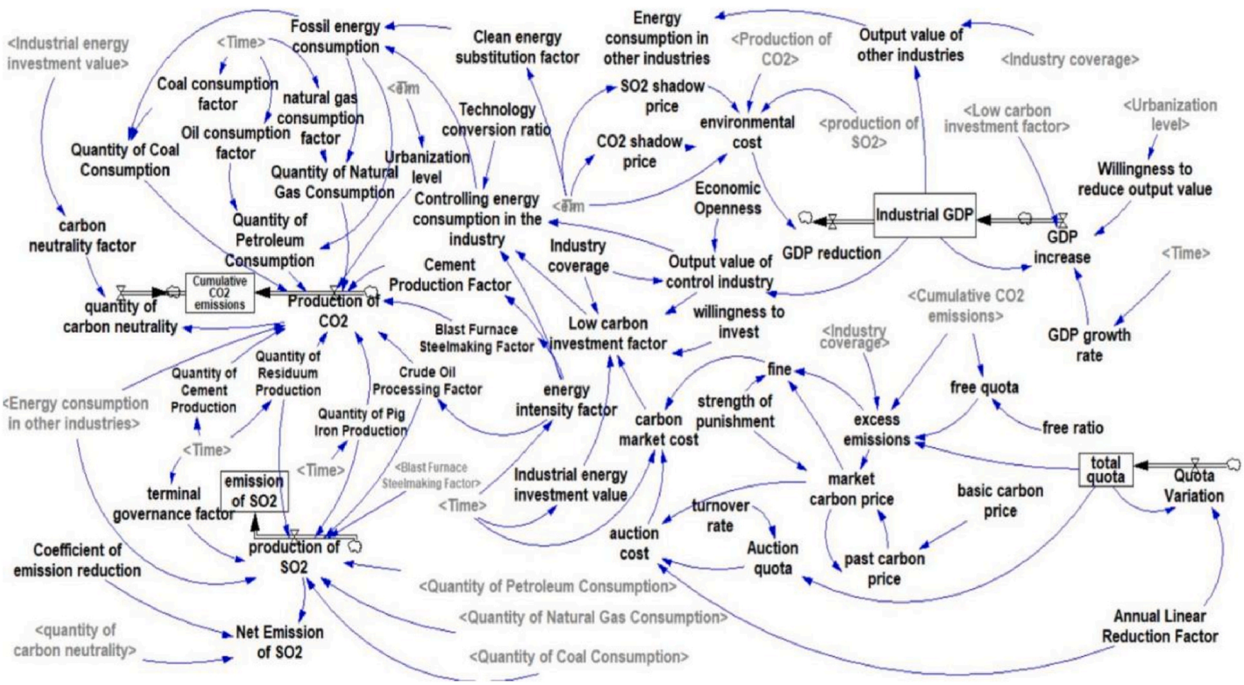


Fig. 1. Stock flow diagram of 3E model of System Dynamics.

Table 1
System variable sorting.

System name	Horizontal variable	Rate variable	Auxiliary variable
Carbon emissiont rading system	total quota	Quota Variation	Annual Linear Reduction Factor, auction cost, auction quota, basic carbon price, carbon market cost, excess emissions, fine, free quota, free ratio, market carbon price, past carbon price, strength of punishment, turnover rate.
Coupled economic and energy system	Industrial GDP	GDP increase, GDP reduction	Blast Furnace Steelmaking Factor, carbon neutrality factor, Cement Production Factor, Clean energy substitution factor, Coal consumption factor, Controlling energy consumption in the industry, Crude Oil Processing Factor, Economic Openness, Energy consumption in other industries, energy intensity factor, Fossil energy consumption, GDP growth rate, Industrial energy investment value, Industry coverage, Low carbon investment factor, natural gas consumption factor, Oil consumption factor, Output value of control industry, Output value of other industries, Quantity of Cement Production, Quantity of Coal Consumption, Quantity of Natural Gas Consumption, Quantity of Petroleum Consumption, Quantity of Pig Iron Production, Quantity of Residuum Production, Technology conversion ratio, Urbanization level, willingness to invest, Willingness to reduce output value.
Atmospheric environment system	Cumulative CO_2 emission, Cumulative SO_2 emission	Production of CO_2, Production of SO_2	CO_2 shadow price, Coefficient of emission reduction, environmental cost, Net Emission of CO_2, Net Emission of SO_2, quantity of carbon neutrality, SO_2 shadow price, terminal governance factor.

main formulas are shown in equations (1)–(4).

$$w(i) = \frac{f(i+1) - f(i)}{f(i)} \tag{1}$$

In the above formula, $w(i)$ represents the growth rate of industrial GDP in year i; $f(i+1)$ represents the industrial GDP in year $i+1$; $f(i)$ represents the industrial GDP in year i.

3.3.2. Arithmetic mean method

The method of arithmetic mean based on the arithmetic mean calculated from the statistical data over time as a reasonable estimate of a parameter. In the model, the parameters that apply this method include the end governance factor and the percentage of low-carbon investment. The main reference formula is as follows:

$$\ddot{x} = \frac{1}{n}\sum_{i-1}^{n}(x_i) \tag{2}$$

In the above formula, $\ddot{x}$ represents arithmetic mean of calculated parameter; x_i represents the value of calculated parameter in year i.

3.3.3. Formula derivation method

The energy pollution coefficient is estimated by determining the relationship between the consumption of each energy and the emissions, and the energy pollution coefficient between the energy subsystem and the environment subsystem can be derived using equations (3) and (4).

$$WRSS = \sum_{i \in I} v_i \bullet p_i \tag{3}$$

$$u_i = \frac{v_i}{\sum_{i \in I} v_i} \tag{4}$$

In the above formula, $WRSS$ represents energy pollution coefficient; u_i represents the weight of the ith energy emission component; p_i represents the pollutant emission from the ith energy source; and v_i represents the consumption of the ith energy.

3.3.4. Regression analysis

Regression analysis, a statistical analysis method is used to estimate or predict the observed value of a random variable using a group of non-random variables. Multiple linear regression mainly investigates the correlation between the random variable Y and the non-random variables $x_1, x_2, x_3, \cdots\cdots x_k$. The model estimates the energy consumption of control and emission industry and other industries using the regression method.

3.3.5. fitting method

The fitting method is to bring all possible values of the target variables into the model, perform calculations in the System Dynamics software, and select the most scientifically reliable parameter value as the initial value. In this study, the proposed method is used to determine the potential values for the clean energy factor, etc.

The selection of the coefficients is an important part of determining the equation, and the significant coefficients in this study are set based on the following: coal carbon production factor, oil carbon production factor, natural gas carbon production factor, cement production carbon production factor, blast furnace steel production factor, crude oil processing carbon production factor and other parameters are set mainly from the IPCC National Greenhouse Gas Inventory Guidelines; coal sulphur production factor, oil sulphur production factor, natural gas sulphur production factor, natural gas sulphur production factor, high carbon oil production factor, high carbon oil production factor, etc. The setting of the sulphur production factor for coal, sulphur production factor for oil, sulphur production factor for natural gas, sulphur production factor for cement production, sulphur production factor for blast furnace steelmaking and sulphur production factor for crude oil processing are mainly taken from the Handbook on Industrial Pollutant Generation and Emission Factors; the setting of the coal consumption factor, oil consumption factor, natural gas consumption factor, energy intensity factor and end-of-pipe control factor are mainly based on the regular summary of historical data; the annual linear reduction factor, auction ratio, penalty intensity, auction price and other. The setting of parameters such as annual linear reduction factor, auction ratio, penalty, auction price, etc. is mainly based on the operation of the pilot carbon market.

Based on the five categories of methods described above, the fundamental equations for this system are represented by equations (5)–(8):

Production of CO_2 = Quantity of Coal Consumption*2.7412+Quantity of Petroleum Consumption*2.1358+ Quantity of Natural Gas Consumption*1.6262+Quantity of Cement Production*Cement Production Factor*0.3954+Quantity of Pig Iron Production*Blast Furnace Steelmaking Factor*1.35+Quantity of Residuum Production*Crude Oil Processing Factor*2.1358+Urbanization level*500000 + 0.893*Energy consumption in other industries+(4e+06) (5)

Production of SO_2 = (Quantity of Coal Consumption*0.0336+Quantity of Petroleum Consumption*0.00525+Quantity of Natural Gas Consumption*0.000474+Quantity of Pig Iron Production*Blast Furnace Steelmaking Factor*0.000131+Quantity of Residuum Production*Crude Oil Processing Factor*0.00112 + 0.012* Energy consumption in other industries) *Terminal governance factor/100000 + 1 (6)

Table 2
Values and basis for the coefficients in the system dynamics 3E model.

Parameter	Value	Basis for value
Carbon production coefficient of coal	2.7412 ton/tce	Refer to the IPCC Guidelines for National Greenhouse Gas Inventories for carbon emission factors for various energy sources and processes
Carbon production coefficient of oil	2.1358 ton/tce	
Carbon production coefficient of natural gas	1.6262 ton/tce	
Carbon production coefficient of cement production	0.3954 ton/ton raw meal	
Carbon production coefficient of blast furnace steelmaking	1.35 ton/ton pig iron	
Carbon production coefficient of crude oil processing	2.1358 ton/ton residual oil	
Sulphur production coefficient of coal	0.0336 ton/tce	Refer to the Industrial Pollutant Generation and Emission Factors Manual for sulphur emission factors for various energy sources and processes
Sulphur production coefficient of oil	0.00525 ton/tce	
Sulphur production coefficient of natural gas	0.000474 ton/tce	
Sulphur production coefficient of blast furnace steelmaking	0.00013 ton/ton pig iron	
Sulphur production coefficient of crude oil processing	0.00112 ton/ton residue	
Carbon dioxide shadow price	100 yuan/ton	Referring to the findings of Chen, S.Y for the shadow price of carbon dioxide [18], the validity of its non-linearity was dealt with using a table function
Sulphur dioxide shadow price	1112 yuan/ton	Referring to the results of Yuan, P [19] for the shadow price of sulphur dioxide, the validity of its non-linearity was dealt with using the table function
Initial value of total quota	3511.27 million tons	Due to the lack of enterprise-level data, this study assumes that all enterprises in the emission-controlled sectors are included in the carbon market using the emissions of the emission-controlled sectors in 2019 as the total number of allowances, using the power sector as an example here
Coal consumption coefficient	97.70 %	Based on the total energy consumption and coal consumption data fitted from the China Energy Statistics Yearbook in previous years, here is an example of data from the power sector in 2018
Oil consumption coefficient	0.0047 %	Based on the total energy consumption and oil consumption data fitted from the China Energy Statistics Yearbook in previous years, here is an example of the data for the power sector in 2018
Natural gas consumption coefficient	2.10 %	Based on the total energy consumption and natural gas consumption data fitted from the China Energy Statistics Yearbook in previous years, here is an example of the data for the power sector in 2018
Energy intensity factor	4900 yuan/tce	Based on the total energy consumption and GDP data fitted from the China Statistical Yearbook in previous years, here is an example of the data for the power sector in 2018
Terminal governance factor	0.46 %	Based on the China Environment Statistical Yearbook, the amount of sulphur dioxide produced and the amount of carbon dioxide emitted are calculated by fitting the data of the power industry in 2018.

Controlling energy consumption in the industry= (Energy intensity factor*Output value of control industry-Technology conversion ratio*Low carbon investment factor*Output value of control industry*energy intensity factor) *1000 (7)

Low carbon investment factor = Willingness to invest*carbon market cost/Output value of control industry + Industrial energy investment value*industry coverage/Output value of control industry (8)

3.4. Parameter determination

Combining the structural characteristics of the system and the dependencies between the variables, this study determines the relevant parameters by reviewing the literature and numerical fitting. The values and sources are shown in Table 2.

3.5. Model testing

After establishing the model, this study employs industrial GDP, CO_2 emissions and SO_2 emissions as the test variables and substitutes historical statistics from 2016 to 2020 to compare with the simulated data, and the results are shown in Table 3. Data on industrial GDP output are from the China Statistical Yearbook 2022 compiled by the National Bureau of Statistics, data on carbon dioxide emissions are from the World Bank's Data bank (provided by the Carbon Dioxide Information Analysis Centre of the Environmental Sciences Division of the Oak Ridge National Laboratory, Oak Ridge, Tennessee, United States of America), and data on sulphur dioxide emissions are from national data published by the National Bureau of Statistics of China.

Table 3 shows that the relative error between the actual data and the Vensim software simulations is within ±15 %, which meets the requirements of the System Dynamics model validity test and reflects that the model fits well with the 3E system and can be used to predict the synergistic emission reduction effect of the national carbon market.

4. Result and discussion

4.1. Simulation analysis of the baseline scenario

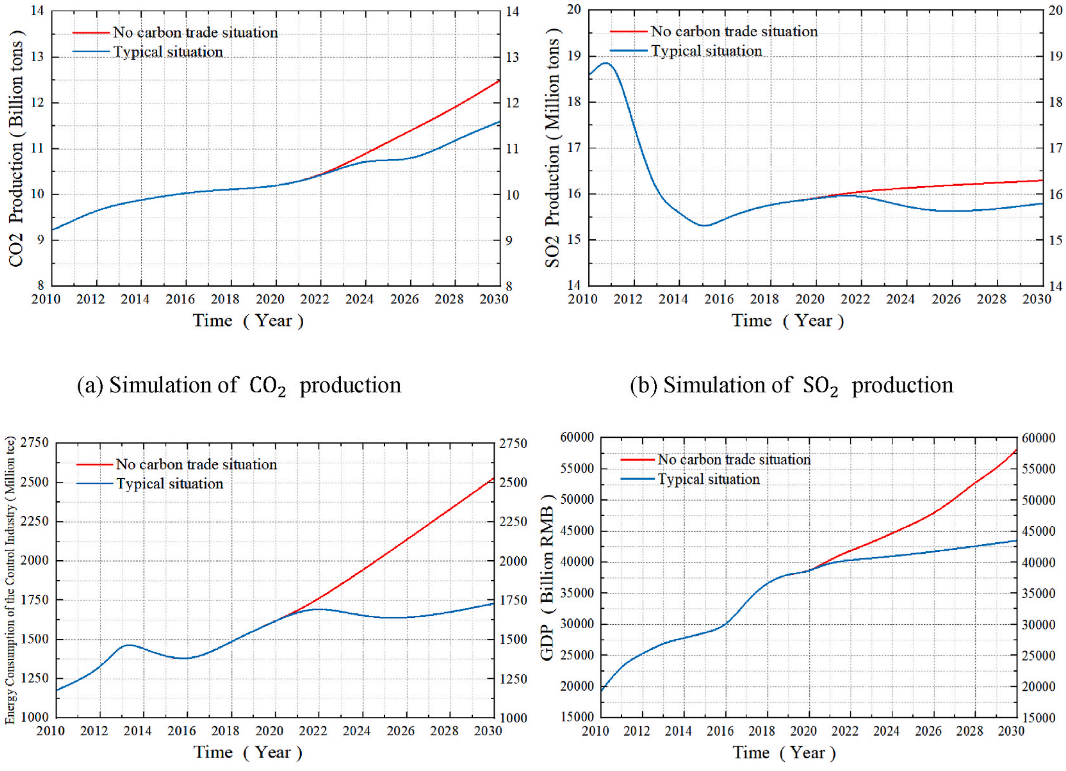
Based on the model test, the basic behavior of the model was simulated with the current parameter settings. The model was programmed to run from 2010 to 2030 with a step size of 1 year, and was separated into a no carbon market scenario (BAU scenario) and a typical scenario where the national carbon market operates with the most common mechanism design of the pilot carbon market. In the no carbon market scenario, the carbon market module is disconnected from the rest of the system, while the annual linear reduction factor is set at 2.5 % (based on China's target of a 65 % reduction in carbon intensity by 2030), the auction ratio at 10 % (based on the usual scenario of the pilot carbon market), and the penalty level at 10 % (based on the typical scenario of the pilot carbon market), while the parameters of industrial GDP growth rate, low carbon investment factor and end-of-pipe governance factor remain unchanged. (based on a typical pilot carbon market scenario), a penalty of 5 times the average carbon price (based on a typical pilot carbon market scenario) and a sectoral coverage of only the power sector (based on the current state of the national carbon market). The outputs of the two scenarios are analyzed in Fig. 2, using industrial GDP, energy consumption in the control sector, CO_2 production and SO_2 production selected as representative indicators for analysis. It can indicate the synergistic effect of GHG and air pollutant emissions reductions, as well as the changes in energy consumption, which is a common driver of both, and the economic cost of the system in terms of various behaviors.

As can be seen from Fig. 2, if no carbon market constraints are placed on China's economy and society, along the current development trend, CO_2 production from industrial sectors will grow slowly at an annual rate of around 4.26 % until 2030 (Fig. 2a), failing to achieve the peak target, while SO_2 production, due to significant reductions starting in 2011 (Fig. 2b), pick up in 2016 and experience a plateau period after 2020, neither significantly growing nor further reducing in emissions. Industrial energy consumption, represented by the power sector, has been maintaining a growth rate of around 9.71 % (Fig. 2c), which is a primary cause of the continued growth in carbon emission and the inability to reduce pollutant emission further.

Simulation results for a typical scenario show that energy consumption levels increase in equal measure to industrial GDP growth (Fig. 2d), with carbon dioxide and sulphur dioxide emissions strongly linked to industrial GDP, and without environmental constraints,

Table 3
error analysis of key indicators for model validation.

	Year	2016	2017	2018	2019	2020
Industrial GDP Simulation Results (billion RMB)	Real value	24540.6	27511.9	30108.9	31185.9	31290.3
	Simulated value	23781.5	26436.5	28693.5	29460.9	29280.2
	Relative error	−3.09 %	−3.91 %	−4.70 %	−5.53 %	−6.42 %
CO_2 emissions Simulation Results (kiloton)	Real value	9860914	10089273	10,567,262	10,762,824	10,944,686
	Simulated value	10,009,873	10,012,983	10,014,760	10,028,978	10,004,987
	Relative error	1.51 %	−0.76 %	−5.22 %	−6.82 %	−8.59 %
SO_2 emission Simulation Results (kiloton)	Real value	8550	6110	5160	4570	3180
	Simulated value	9460	6850	5340	4870	3310
	Relative error	10.64 %	12.11 %	3.49 %	6.56 %	4.01 %



(a) Simulation of CO_2 production

(b) Simulation of SO_2 production

(c) Simulation of Industrial energy consumption

(d) Simulation of industrial GDP

Fig. 2. Baseline scenario simulation results.

both emissions continue to grow without effective curbs. The inclusion of the power sector in the national carbon market, as expected, will result in lower CO_2 and SO_2 emissions between 2020 and 2030 compared to the period without a carbon market, reflecting the ability of the carbon market to promote synergistic emissions reductions of GHG and air pollutants. However, due to its inclusion of a single sector and limited regulatory intensity, the contribution to both carbon and pollutant emissions reductions is limited, with only a relative reduction of around 3 %. By examining the trend in energy consumption, it is clear that this is due to the limited reduction in energy consumption in the emission-controlled sectors under the typical scenario of the carbon market, which initially shows a downward trend in energy consumption, but then slowly rises with GDP growth after 2024, and therefore fails to achieve a more significant synergistic effect in terms of pollution and carbon reduction. As a result, a more effective carbon market mechanism design needs to be explored to incentivise emission-controlled sectors to reduce energy consumption and achieve more significant synergistic emission reduction effects.

4.2. Multi factor coupling analysis under policy regulation

4.2.1. Carbon market scenario setting

In the above, the impact of national carbon trading on the economy, energy and environment has been built using a System Dynamics model, and the model test has been conducted with the help of historical data. In the following, based on the constructed model, a simulation analysis will be carried out by simulating 15 segmented carbon trading scenarios to investigate the impact of different industry coverage, carbon trading prices and free ratios on the national economic level and CO_2 emissions respectively.

Through a control variables research approach, varying the remaining variables in the system under the condition that they are constant. The specific data of one or more variables are simulated using Vensim software for multiple scenarios of the strategy. In this study, the control variable method is used to divide the policy simulation scenarios into three categories: A, B and C.

In the scenario of Category A policy simulation, the benchmark carbon price is maintained at 30 yuan/ton, the ratio of free is maintained at 0.2, and the industry coverage is successively set as 0.2, 0.4, 0.6, 0.8 and 1.0, with corresponding numbers A1, A2, A3, A4 and A5.

In the scenario of Category B policy simulation, the industry coverage remains 0.2, the proportion of free remains 0.2, and the benchmark carbon price is successively set as 30, 50, 100, 200, 400 (yuan/ton), with corresponding numbers B1, B2, B3, B4 and B5.

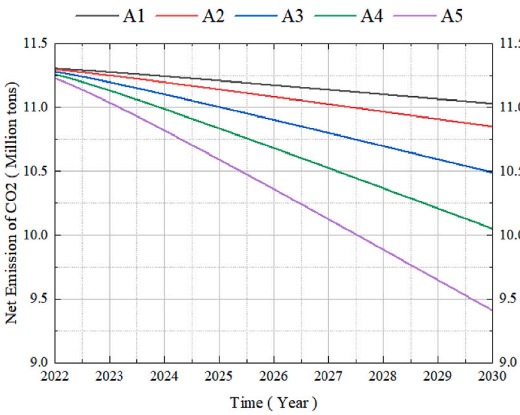
In the scenario of Category C policy simulation, the industry coverage remains 0.2, the benchmark carbon price remains 0.2, and the free ratio is successively set as 0.1, 0.2, 0.4, 0.6 and 0.8, with corresponding numbers C1, C2, C3, C4 and C5.

According to the particular settings of the three primary categories of scenarios in the previous subsection, Vensim software was used to simulate the dynamics model of the national carbon trading system. By separately analyzing the simulation results of adjusting the coverage of industries, the price of carbon trading and the proportion of free allowances, with a view to exploring the impact of different carbon trading policy formulation on the economic level and the total amount of carbon dioxide emissions.

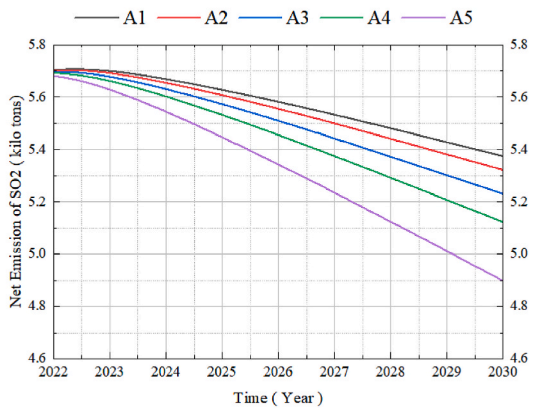
4.2.2. Analysis of carbon market scenarios in category A

As the coverage of the carbon market continues to expand and more industries are included in the carbon market, businesses will take a series of carbon reduction measures to minimise the cost of the carbon market in an orderly and regulated carbon market environment, thus objectively promoting the continuous reduction of CO_2 and SO_2 emissions. However, at the same time, the expansion of carbon market coverage will also lead to an increase in the overall cost of carbon reduction, which will have a dampening effect on the development of industrial GDP. The effects of sectoral coverage on CO_2 and SO_2 emissions and industrial economic growth is depicted in Fig. 3, where in 2030 the net CO_2 emissions are reduced from 11.03 to 9.41 million tons (Fig. 3a), SO_2 emissions from 5.37 to 4.91kilo tons (Fig. 3b) and industrial GDP from 41540 to 37860 billion RMB (Fig. 3c) when the sectoral coverage is adjusted from 0.2 to 1.0.

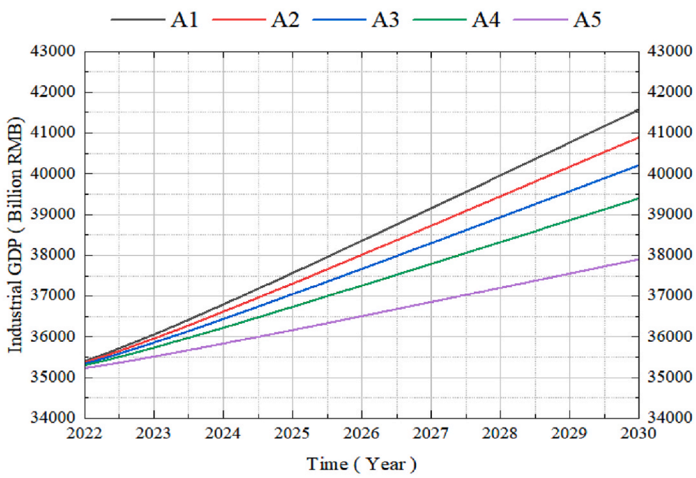
It shows that increasing the sectoral coverage of the carbon market can significantly cut net CO_2 emissions. Although the expansion of carbon market coverage reflects a certain degree of inhibitory effect on industrial GDP, the effect is minimal compared to the impact of the next carbon market elements - carbon trading price and free ratio - and thus the overall view is that the expansion of carbon market has less negative impact on industrial economic development.



(a) Simulation of net CO_2 emissions



(b) Simulation of net SO_2 emissions



(c) Simulation of industrial GDP

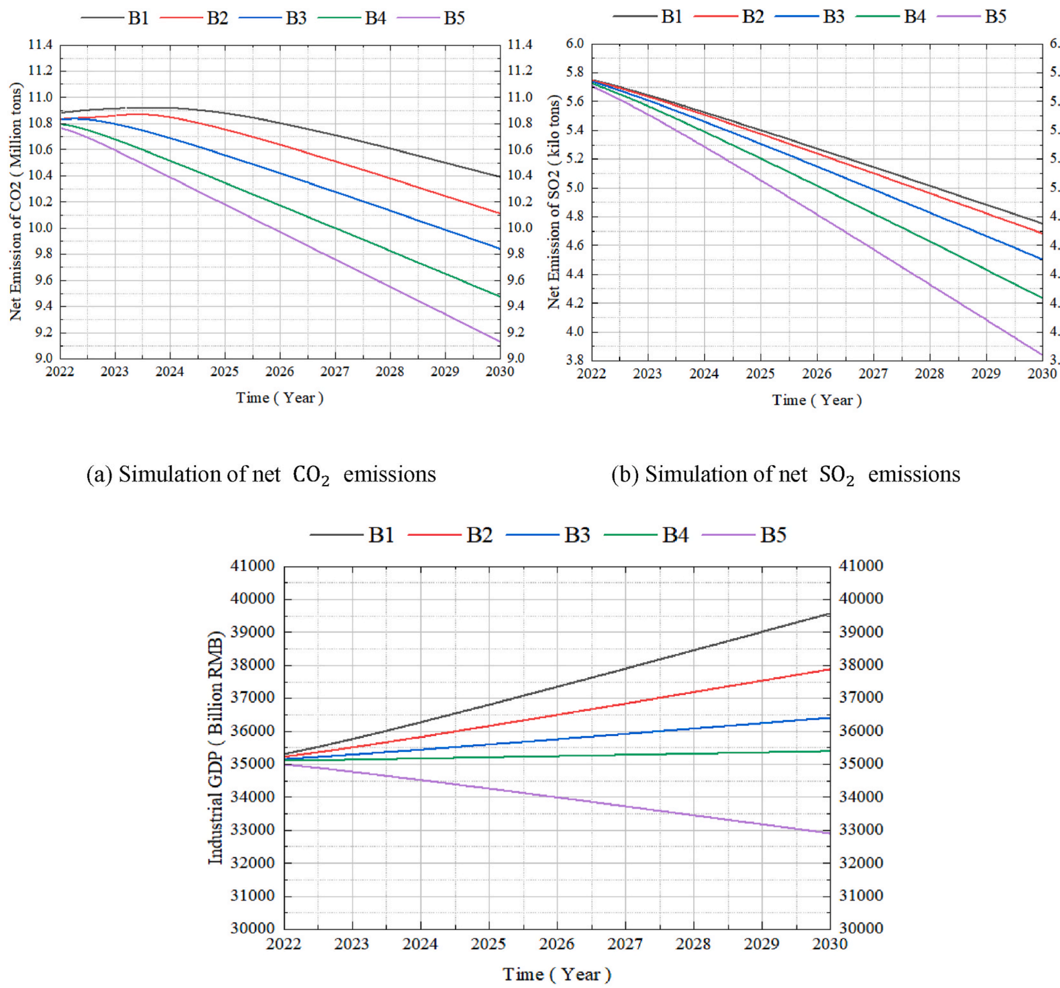
Fig. 3. Net CO_2 emissions, net SO_2 emissions, industrial GDP curves for scenarios A1-A5.

4.2.3. Analysis of carbon market scenarios in category B

The establishment and adjustment of carbon trading prices in the carbon market mechanism is another core key policy factor. If the price of carbon trading were too high, it would not be conducive to economic equilibrium and would seriously affect the smooth development of industrial GDP and reduce the well-being of the human society. However, if the price of carbon trading were too low, industries would not have enough motivate to control and reduce emissions, making it difficult to achieve the goal of effective control of CO_2 emissions. The impact of carbon trading price on CO_2, SO_2 emissions and industrial economic development is shown in Fig. 4, where in 2030 the net CO_2 emissions are reduced from 10.40 to 9.31 million tons (Fig. 4a), SO_2 emissions from 4.76 to 3.83 kilo tons (Fig. 4b) and industrial GDP from 39580 to 32970 billion RMB (Fig. 4c) when the carbon trading price is adjusted from RMB 30 to 400 per tonne. At the same time, if the price of carbon trading were set too high, it would be challenging for the industrial economy to maintain regular development.

4.2.4. Analysis of carbon market scenarios in category C

The free ratio is the proportion of the total number of allowances that companies can emit CO_2 for free when the government allocates the amount of carbon allowances. Obviously, the lower the free ratio, the higher the cost to industries for greater participation in carbon trading, otherwise the excess CO_2 emissions will face strong penalties in the form of carbon market fines, which have a negative impact in industrial GDP development; however, too high a free ratio will result in insufficient incentive for industries to control emissions and reduce emissions, which will prevent them from achieving their intended emission reduction targets. The impact of the free ratio on CO_2, SO_2 and industrial economic development is shown in Fig. 5, where in 2030 the net CO_2 emissions drop from 10.03 to 9.32 million tons (Fig. 5a), the net SO_2 emissions drop from 4.24 to 3.35 kilo tons (Fig. 5b), and the industrial GDP drops from 38580 to 31507 billion RMB (Fig. 5c) when the free ratio is reduced from 0.8 to 0.1. It can be seen that the inhibitory effect of a low free



(a) Simulation of net CO_2 emissions

(b) Simulation of net SO_2 emissions

(c) Simulation of industrial GDP

Fig. 4. Net CO_2 emissions, net SO_2 emissions, industrial GDP curves for scenarios B1–B5.

ratio on industrial economic development is more pronounced than the effect of emission control. When the free ratio is too low, the negative impact on the macro-economy will be significant, so it must be used in conjunction with other policy factors in order to optimize the benefits of the dual objectives of controlling emissions and ensuring economic development.

A comprehensive analysis of scenarios A, B and C shows that, for the carbon market at this time, among the series of policy instruments discussed, the policy instrument that reduces emissions the most, suppresses industrial GDP the least and has the best overall effect is the adjustment of the carbon market sector coverage.

5. Conclusions and policy implications

5.1. Conclusions

Based on the theoretical analysis of the synergistic emission reduction pathways of the carbon market, this study has used System Dynamics to construct an 3E model of the synergistic emission reduction effect of the carbon trading system and explored the synergistic emission reduction effect of the carbon market mechanism design.

It has been demonstrated that the carbon market can stimulate the synergistic emission reduction of GHG and air pollutants by simulation. Such synergistic emission reductions, however, are constrained by the current national carbon market design. This study further simulates the impact of the carbon market system on synergistic emissions reduction under different scenarios of industry coverage, benchmark carbon price and free allowance ratio.

The result of simulation shows that expanding the coverage of the carbon market could be effective in significantly reducing net CO_2 and SO_2 emissions, while having less negative impact on industrial GDP. Promoting carbon price would be beneficial in reducing

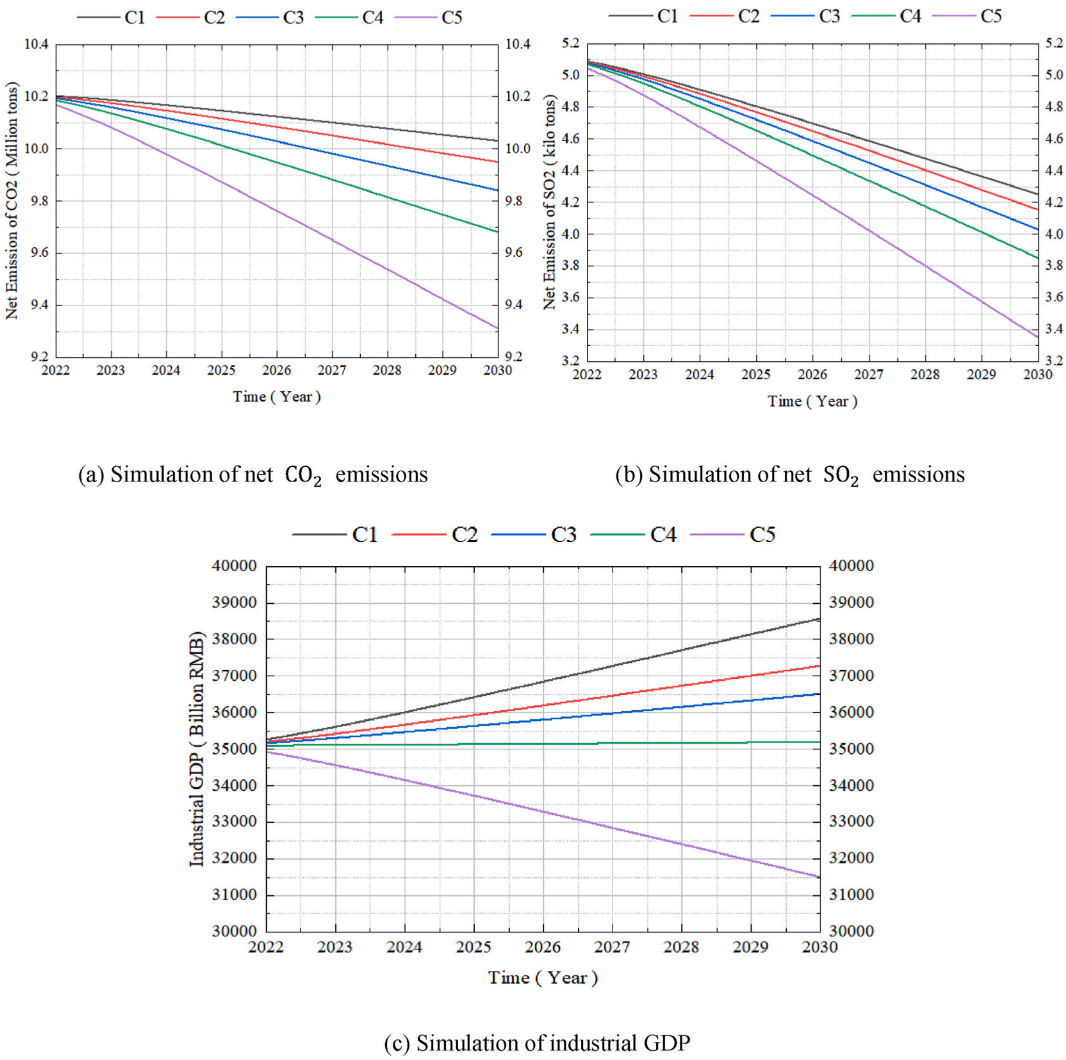


Fig. 5. Net CO_2 emissions, net SO_2 emissions, industrial GDP curves for scenarios C1–C5.

CO_2 and SO_2 emissions. However, if the price of carbon trading is set too high, industrial GDP would struggle to sustain its usual rate of growth, which would harm the macroeconomy. Similarly, lowering the proportion of free allowances would also result in effective control of CO_2 and SO_2 emissions, but at the same time the rate of decline in industrial GDP would also increase.

Regarding the effect of carbon market on the synergistic reduction of SO_2, our findings are in line with those of the previous researchers [7], and it is again argued that the carbon market will have a certain inhibitory effect on the macro-economy through the price mechanism. Once the industry is regulated by the carbon market, it will show different degrees of negative feedback on the cost of carbon price, whether it is directly affecting the carbon price, or reducing the proportion of free quota issuance, or adjusting the carbon price through the supply and demand relationship, which will ultimately be reflected in the increase of the cost of the industry to be regulated and inhibit its incentive to produce, resulting in a decline in the value of output.

Compared to previous research on element design of China's Emissions Trading System pilot from the perspective of environmental effects, this study investigates the industry coverage in a more detailed and quantitative way and attempts to analyze the detailed transmission between the specific setting of the carbon market and the synergies effect, which gives certain insights into the design of the mechanism of the carbon market.

Therefore, taking a systemic view of the carbon market mechanisms to synergize and rationalize is quite necessary for achieving effective emissions reductions and ensuring smooth economic development. A well-designed national carbon trading market is not only crucial for tackling climate change, but it also has the potential to reduce air pollution in a coordinated manner.

5.2. Policy implications

In order to bring the synergistic effects of carbon markets into play more effectively, this study proposes the following policy recommendations:

The potential for synergistic emission reduction of carbon market needs to be understood with a focus on the crucial role that industry inclusion plays in multi-objective optimization for synergistic emission reduction.

Firstly, the overlaps between origins of GHG and air pollutants need to be explored, which will benefit for setting criteria for evaluating the synergistic emission reduction effect of the carbon market.

Secondly, it is essential for policy makers to guarantee both improved system coverage and the establishment of accurate boundary. The fundamental information of accounting and monitoring of emissions needs to be managed by enterprises, and the life-cycle differences of various emissions in the processes of energy use, industrial production, and end-of-pipe treatment should be distinguished.

Thirdly, the coverage of industries in the carbon market should be set reasonably. If it were impractical to include all members of certain industry in one go, some large enterprises could be included to compensate for the lack of coverage in the carbon market and to boost the carbon market's synergistic emission reduction efforts.

5.3. Further discussion

Due to the multidimensional complexity of System Dynamics, this study has not yet distinguished the incentive effects of carbon market on various industries in detail, and the optimal emission reduction paths and the optimal inclusion order of different industries in the carbon market deserve to be further investigated. Besides, due to the fact that there are multiple games in the design of carbon market mechanism, the System Dynamics shall be used in combination with other methods, such as game theory, in order to simulate the responses of multi-stakeholders more accurately. These issues will be investigated further in future studies.

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Data availability statement

Data associated with the study has not been deposited into a publicly available repository and data will be made available on request.

CRediT authorship contribution statement

Lan Yi: Funding acquisition, Project administration, Supervision. **Zhi-peng Yang:** Data curation, Methodology, Writing – original draft. **Zhi-kai Zhang:** Data curation, Methodology, Writing – original draft. **Li Yang:** Data curation, Formal analysis, Methodology. **Wei Deng:** Conceptualization, Formal analysis, Writing – review & editing.

Declaration of competing interest

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

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