Energy and Climate Management
https://doi.org/10.26599/ECM.2024.9400002

Review

An environmental CGE model of China's economy: Modeling choices and application

Yu Liu[1,2,✉], Nenggao Zhu[3,4], Meifang Zhou[5], Xin Wen[6], Lingyu Yang[3,4], Xinbei Li[3,4], Jinzhu Zhang[1]

[1]*College of Urban and Environmental Sciences, Peking University, Beijing 100871, China*
[2]*Institute of Carbon Neutrality, Peking University, Beijing 100871, China*
[3]*School of Public Policy and Management, University of Chinese Academy of Sciences, Beijing 100049, China*
[4]*Institutes of Science and Development, Chinese Academy of Sciences, Beijing 100190, China*
[5]*School of Economics, Beijing Technology and Business University, Beijing 100048, China*
[6]*School of Economics and Management, Beihang University, Beijing 100191, China*

Received: 30 December 2023; Revised: 24 January 2024; Accepted: 7 March 2024

ABSTRACT

This article discusses the expansion and application of computable general equilibrium (CGE) models as significant policy guidance tools for pollution reduction and emission control objectives. Based on the theoretical framework of the Australian school of CGE modeling, we have developed an integrated model that encompasses energy, environment, and economy. This model incorporates energy, environmental, and emission introduction processes, closure mechanisms, and dynamic adjustments. Before simulations, we typically conduct Back-of-the-envelope (BOTE) analyses and validate the accuracy of economic theory judgments and model simulation results through comparative analysis. The article also summarizes our research based on the CGE model, including investigations into differences under various carbon tax revenue policies, comparisons between single-region and multi-region carbon market mechanisms, rebound effects from energy efficiency improvements, impacts of different environmental tax strategies, and the cost-neutral setting of carbon neutrality goals. These findings demonstrate the widespread application and significance of CGE models in theoretical research and policy formulation.

KEYWORDS

Computable general equilibrium model, economic closure, investment mechanism, back-of-the-envelope.

As of September 2023, over 150 countries have committed to carbon neutrality, covering more than 80% of the world's carbon dioxide (CO_2) emissions, GDP, and population[1]. However, climate change strategies must simultaneously support economic and social development goals. Due to the inherent interdependence of economic structures, energy and environmental policies aimed at reducing greenhouse gas emissions often have significant effects on variables such as price, quantity, and economic structure. Emission reduction efforts have an impact on both high-emission sectors and generate systemic effects on the economy and society through industrial connections and income effects[2]. In this context, the cost-benefit of emission reduction measures, resulting distributional effects and equitable transformation are increasingly emphasized in society. Researches have been published in top international journals such as *Nature* and *PNAS*[3–5].

The general equilibrium framework of the computable general equilibrium (CGE) model is used in cost-benefit analysis in the field of energy and environmental policy[2, 6–8]. Based on standard micro- and macroeconomic theories, the CGE model establishes quantitative connections between various sectors of the economy, enabling the examination of both direct and indirect effects resulting from exogenous changes in the economy, as well as their global impacts on the overall economy. Its characteristics of multiple economic agents, various industrial sectors and diverse groups of households, enable detailed analysis of intra-industry redistribution and resident welfare. This level of detail is difficult to achieve with other methods [9, 10]. Compared to econometric models, the CGE model can study the potential impacts of exogenous shocks without historical data and frequent changes in economic mechanisms. In contrast to the input-output model, CGE models have clear settings of economic agents' behaviors, emphasizing the role of resource constraints and price mechanisms, which surpass the fixed input-output relationships of the traditional input-output model. The beforehand analytical and detailing capabilities of CGE models are widely recognized by scholars as supportive of policy development[9, 11].

However, compared with the widespread application of CGE models, few articles provide detailed disclosure of model equations, data processing, solution methods, and how to interpret simulation results. This leads to the CGE model often being regarded as a "black box"[12, 13]. Research consistently acknowledges that the significant differences, difficulties in comprehension, and irreproducibility of CGE model results mainly arise from the opacity of model equations and data. A few model experts have also recognized this issue and attempted to publish papers addressing the equations and data used in their CGE models[8, 12, 13]. This is also a crucial reason for conducting this study. In this paper, we elaborate on the main modules and equations of the Chinese environmental CGE model used, economic and emission database development, macro closure settings, solution methods, and interpretation of simulation results. Our model is constructed based on the CGE model theory of the Australian Center of Policy Studies[14], main features include:

✉Address correspondence to E-mail address: yu.liu@pku.edu.cn

(1) Following the idea of Johansen[15], the nonlinear relationship between economic variables is converted into a rate of change form, thereby converting the nonlinear equations into a linear equation that is easy to solve by computers. (2) According to the impact amplitude, flexible selection of various solution methods, such as Johansen's one-step method, Euler's multi-step method, etc., to achieve a balance between solution speed and accuracy. (3) Providing a theoretical paradigm to explain simulation results. The underlying transmission mechanism of the CGE model can be expressed using a set of simplified equations defined as BOTE. In the article, we elaborate on how to perform BOTE analysis on a given exogenous shock to obtain theoretical judgments based on economic theory, which provides a basis for interpreting and understanding actual simulation results.

In the rest of the paper, Section 1 introduces the behavioral equations of various economic agents in the model, macroeconomic closure, dynamic mechanisms, and solution methods in this model. Section 2 details the construction methods and data sources for economic and emission databases, along with the establishment of significant parameter values. Section 3 provides a detailed demonstration of conducting a BOTE analysis using the example of implementing a carbon tax. In section 4, this article summarizes the research carried out by our team based on this model, primarily focusing on model extensions and potential future research.

1 Model structure

This model is an environmental CGE model jointly developed by Peking University and the CoPS (Centre of Policy Studies) of Victoria University. This model includes three blocks (economy, energy, and environment), six economic agents (producers, investors, households, government, export, and inventories), and three primary factors (labor, capital, and land). Multi-layered nested production functions are used to show the linkages of substitution between various inputs. This model, which is based on input-output and Walrasian general equilibrium theory, makes certain assumptions about the world. These include perfect competition in markets, constant returns to scale in production, optimal behavior for different economic agents, and so on. Specifically, under resource constraints, producers determine optimal supply quantities based on principles of cost minimization or profit maximization, while consumers choose the best demand quantities based on utility maximization principles. In the end, when the model achieves equilibrium in product markets, factor markets, capital markets, government budgets, household finances, and international markets, it yields equilibrium prices and quantities for products, leading to an overall balanced economic state[14, 16, 17].

1.1 Production block

The production block consists of input decision and output distribution. The optimal input decision is determined by the principle of cost minimization, using the Constant Elasticity of Substitution (CES) function to represent incomplete substitution. The distribution of output between domestic and export markets is determined by the principle of profit maximization, using the Constant Elasticity of Transformation (CET) function. This function decides the optimal allocation of different products within total output, as well as the optimal distribution proportions of products in domestic and foreign markets.

$$Y1 = A1[\delta_1(A1_1X1_1)^{\rho} + \delta_2(A1_2X1_2)^{\rho}]^{\frac{1}{\rho}} \tag{1}$$

$$X1_1 = \left(\frac{A1^{\rho}\delta_1 P1Y1}{P1_1}\right)^{1/(1-\rho)} Y1 \tag{2}$$

$$X1_2 = \left(\frac{A1^{\rho}\delta_2 P1Y1}{P1_2}\right)^{1/(1-\rho)} Y1 \tag{3}$$

where $Y1$ is output, $X1_1$ and $X1_2$ are two input factors, δ_1 and δ_2 are the shares of input factors $X1_1$ and $X1_2$, with $\delta_1 + \delta_2 = 1$. $P1_1$ and $P1_2$ are the price of two inputs. $P1$ is the average price of two inputs. $A1$, $A1_1$, and $A1_2$ are technological progress coefficients. When $\rho \in (-\infty, 0) \cup (0, 1)$, Eq. (1) is the standard form of the CES function. When $\rho > 1$, Eq. (1) is CET function. Eqs. (2) and (3) depict the production relationship constructed through the CES production function and the demand functions for the two inputs.

At the top nesting, the Leontief production function is employed to characterize the input relationships among energy and primary factor composite products, as well as non-energy intermediate inputs (Figure 1). At the second nesting, the CES function is used to depict the composite relationships among energy and capital composites, labor, as well as land. At the third nesting level, energy products are further divided into electric and non-electric energy. Non-electric energy includes coal composite products, oil composite products, and natural gas composite products, while electric energy consists of various types of electric sectors such as coal power, gas power, nuclear power, hydroelectric power, wind power, solar power, biomass power, as well as electricity transmission and distribution sectors. Within the nested structure of non-electric energy, coal composites, petroleum composites, and natural gas composites are nested using the CES function. At the top-level nesting of electric energy, the electric sector is split into the power generation sector as well as the transmission and distribution sector. The Leontief production function is employed to characterize their substitution relationship, assuming a fixed proportion between electricity production and distribution. At the second nesting, electricity composites consist of the basic power supply and the unstable power supply, and they are nested using the CES function. At the bottom nesting, an incomplete substitution relationship is assumed among the basic power supply and the CES function is used to characterize the substitution relationship among coal power, gas power, hydroelectric power, and nuclear power.

1.2 Demand block

In the model, commodity demand is divided into six categories: household consumption, government consumption, export, investment, margins, and inventories. Figure 2 shows the relationship between the economic agents and commodity demand. Commodities are divided into the normal commodity and the margin commodity. Margin commodity is also regarded as a demand, implying the logistics and services required in the transaction process, called margin goods or margin services. For investment decisions, which mirror production decisions, different investment goods are first synthesized into industry capital stocks based on the Leontief function. Subsequently, the optimal combination of imported and domestically produced investment goods for each investment category is determined based on the principle of cost minimization. Household demand

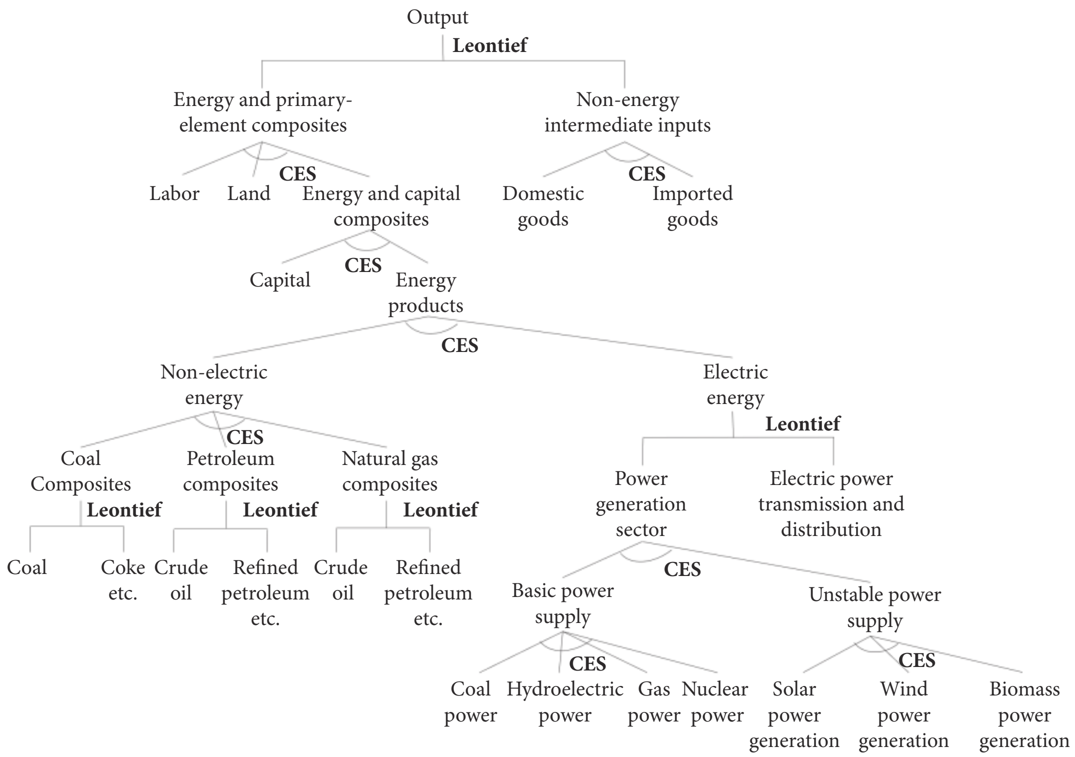


Fig. 1 The production structure with detailed energy industries of the CGE model.

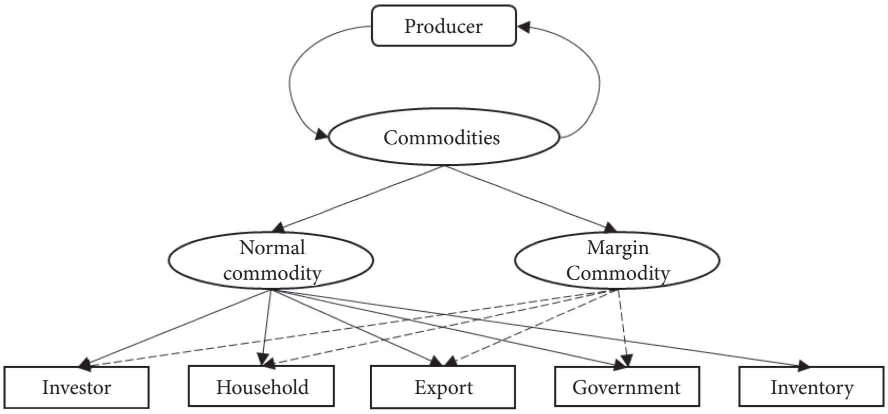


Fig. 2 Economic agents with the commodity demand.

for commodities is primarily influenced by the principles of utility maximization and budget constraints. Household demand is determined by household budgets, preferences, and the buyer prices of domestic and imported goods. The model assumes that the government expenditure follows the changes in household consumption, and margin and inventory depend on changes in commodity demand.

(1) Investment demand. Investment demand comprises two parts, namely the determination of investment amounts in each industry and the allocation of investment. Regarding the determination of investment amounts, the model includes three alternative investment rules. Industries are categorized into those influenced by market forces and those unaffected by market forces. The selection of investment rules for each industry either determines the investment amount in the industry or the share of the industry in total investment. Specific investment rules are detailed in Section 1.6. Concerning the allocation of investment, the top-level nesting involves investors minimizing the total cost of product combinations under the constraint of the Leontief production function. The bottom-level nesting involves investors minimizing the total input cost of imported and domestic products under the constraint of the CES function. The equations are as follows:

$$A2_i I2_i = \mathrm{MIN}\left\{\frac{X2_{ci}}{A2_{ci}}\right\}, (c = 1, \ldots, n) \tag{4}$$

$$X2_{ci} = \mathrm{CES}(X2_{(cs)i}/A2_{(cs)i}), (s = 1, 2) \tag{5}$$

where $I2_i$ is the investment demand of industry i, X_{2ci} is the direct effective input of commodity c in creating capital for industry i, $A2_i$ and $A2_{ci}$ are technological coefficients, variations in $A2$ can be used to simulate technological changes in the capital production units of industry $i.X2_{(c1)i}$ and $X2_{(c2)i}$ are the inputs for capital production in industry i from domestic and imported commodity c. $A2_{(cs)i}$ is an additional set of technological coefficients.

(2) Household consumption. Under budget constraints, domestic households follow the principle of utility maximization to purchase various consumer goods. At the top nesting, the utility function is nested using the Klein-Rubin (Stone-Geary) function for composite goods. At the inner nesting, the CES function is used to depict the substitution between domestic and imported goods. The household consumption of a particular commodity is synthesized from both domestic and imported sources based on the CES function.

$$\mathrm{MAX}U=\frac{1}{Q}\prod_{c\in com}\{X3_c-X3_c^{\mathrm{SUB}}\}^{\beta_c}\ \ \mathrm{s.t.}\,Y=\sum_{c\in com}X3_c*P3_c \tag{6}$$

$$P3_cX3_c=P_cX3_c^{SUB}+\beta_c*\left(Y-\sum\nolimits_{c\in com}P3_cX3_c^{SUB}\right) \tag{7}$$

$$X3_c=\mathrm{CES}(X3_{cs}/A3_{cs}),\ \ (s=1,2) \tag{8}$$

where U is household utility, Y is total expenditure, Q is the number of households. $X3_c$ is the total household consumption of commodity c, $X3_c^{\mathrm{SUB}}$ is the minimum living requirement for commodity c, $P3_c$ is the consumption price, β_c is the luxury consumption share for commodity c. Eq. (6) maximizes the Klein-Rubin (Stone-Geary) non-homothetic utility function under budget constraints, while Eq. (7) is the optimized linear expenditure system (LES). Household consumption of a particular commodity is synthesized from both domestic and imported sources based on the CES function, as shown in Eq. (8). The combined use of Eqs. (6) and (7) ensure that as income increases, the proportion of consumer expenditure on luxury goods relative to total income increases, while the proportion of expenditure on necessities decreases.

(3) Export demand. This model follows the large country hypothesis, where export prices are determined by the export supply and demand of the home country and the rest of the world. Export demand is categorized into tradable and non-tradable goods. Non-tradable goods, due to their small share in the global market or influence from government policy control, have little relationship with their market prices. Tradable goods, constituting a significant share of the global market, exhibit an inverse relationship between export demand and commodity prices. The equation is as follows:

$$X4_c=F4Q_c\times\left(\frac{P4_c}{\mathrm{PHI}\times F4P_c}\right)^{\exp_E^c} \tag{9}$$

where $X4_c$ is the export demand for commodity c, $P4_c$ is the export ex-factory price denominated in the home currency, PHI is the nominal exchange rate under the direct pricing method, serves as the benchmark price, and is exogenously determined in the model. $F4Q_c$ and $F4P_c$ are variables describing the movement of curves' positions, respectively representing movements in the direction of export quantity and price. $\exp_E^c$ is the price elasticity of export demand, which is a negative value.

(4) Government demand. Assuming the government's goal is to improve household welfare. Based on this, the model assumes that government expenditure and household consumption change in the same proportion. The equation is as follows:

$$X5_c=h*X3_c \tag{10}$$

where $X5_c$ is the government expenditure of commodity c, h is the ratio of government expenditure to household consumption.

(5) Inventory demand. Inventory is accompanied by changes in the use of total commodity demand. The equation is as follows:

$$X6_c=X0\mathrm{COM}_c*A6_c \tag{11}$$

where $X6_c$ is the inventory demand of commodity c, $X0\mathrm{COM}_c$ is the total supply of commodity c in the domestic market, $A6_c$ is technological changes in inventory utilization.

(6) Margin demand. Involving five economic entities (producer, household, government, investment, and exports), various margin goods are considered in this model. The model assumes that margin goods exclusively use domestically produced goods. Margin demand depends on the quantity of goods in circulation and the margin consumption coefficient. The equation is as follows:

$$X\mathrm{MAR}_{c,u}=X_{c,u}*\mathrm{AMAR}_{c,u} \tag{12}$$

where $X\mathrm{MAR}_{c,u}$ is the margin demand of commodity c by user u, $X_{c,u}$ is the basic value of commodity c by user u $\mathrm{AMAR}_{c,u}$ is technological changes in margin utilization, when u don't use margin, $\mathrm{AMAR}_{c,u}=0$.

1.3 Energy-environment block

The energy-environment block provides a detailed description of the relationship between the economic activities of producers and the emissions of CO_2 and pollutants, as well as the impact of energy and environmental policies on costs. In the model, the value and quantity of energy inputs of the production sector are linked through a linear relationship. This section also covers the costs that producers need to pay in response to energy and environmental policies, and how these costs are reflected in production decisions and costs.

The amount of carbon emissions and pollutant emissions generated by combustion depends on the changes in the value of energy industry consumption by the main body of economic activities. These emissions will be adjusted accordingly with the changes in energy usage in industry production and residential consumption. The emission of waste gas and wastewater is linked to the output of the emission industry. The specific steps are as follows:

$$\mathrm{PG}_{n,u,e,s}=a_{n,u,e,s}\times\mathrm{DE}_{u,e,s} \tag{13}$$

$$\mathrm{PE}_{g,i}=b_{g,i}\times Q_i \tag{14}$$

$$\mathrm{PW}_{w,u}=c_{w,u}\times Q_u \tag{15}$$

where n denotes the emission of carbon dioxide and waste gas, including SO_2 and NO_x. u denotes users, including 159 industries i and one type of household h. e denotes energy types, including coal, refined oil, natural gas, coke, and oil and gas. s denotes sources, including domestic and imported goods. $w$denotes waste water, including NH_3 and COD. $\mathrm{PG}_{n,u,e,s}$ is the emission n generated by the use of energy e from source s by user u, $\mathrm{DE}_{u,e,s}$ is the energy demand of user u, $a_{n,u,e,s}$ is the combustion emission coefficient of user u, $\mathrm{PE}_{g,i}$ is the process emission of waste gas g generated by industry i, $b_{g,i}$ is the process emission coefficient, and Q_i is the output of industry i. $\mathrm{PW}_{w,u}$ is the wastewater discharge of user u, $c_{w,u}$ is the wastewater process emission coefficient of user u, and Q_u is the output and consumption of industry i and resident h.

In the scenario of taxes or carbon trading, the emission associated with the production of a company will be considered as a part of its production cost. In our model, a virtual consumption tax is used to simulate this cost element. In this way, the policy cost will affect the producer's price level and have an impact on consumer behavior at the product level[8]. The specific form is as follows:

$$P1_{c,s,i} = (1 + t_{c,s,i}) * P0_{c,s} \tag{16}$$

where $P1_{c,s,i}$ is the cost of industry i purchasing commodity c from source s, $P0_{c,s}$ is the price of commodity c sourced from s. $t_{c,s,i}$ is the tax rate that industry i uses for commodity c sourced from s, which includes the carbon tax rate.

1.4 Equilibrium block

Under the model's equilibrium state, two characteristics of the market exist: First is market clearing. For domestic products, domestic production must be equal to the sum of intermediate input, investment demand, household consumption, export, government consumption, inventory, and margin demand. The second is zero profit. The total revenue of goods must be equal to the production input, taxes, and margin costs of goods. Zero profit implies that the total value of consumer purchases is equal to the sum of the producer's value of the commodity at cost, taxes during the sales process, and distribution costs from the production site to the final consumption location. The equations are as follows.

$$\begin{aligned} X0\mathrm{COM}_c = {} & \sum_i X1^{\mathrm{dom}}_{c,i} + \sum_i X2^{\mathrm{dom}}_{c,i} + X3^{\mathrm{dom}}_c + X4_c + X5^{\mathrm{dom}}_c + \\ & X6^{\mathrm{dom}}_c + \sum_u \sum_m XMAR_{c,u,m} \end{aligned} \tag{17}$$

$$X0\mathrm{IMP}_c = \sum_i X1^{\mathrm{imp}}_{c,i} + \sum_i X2^{\mathrm{imp}}_{c,i} + X3^{\mathrm{imp}}_c + X4_c + X5^{\mathrm{imp}}_c \tag{18}$$

$$P1_{c,s,i} * X1_{c,s,i} = P0_{c,s} * X1_{c,s,i} + \mathrm{TAX}_{c,s,i} + \sum_m P0_{c,s} * X\mathrm{MAR}_{c,i,m} \tag{19}$$

where $X0\mathrm{COM}_c$ is the total supply of commodity c in the domestic market, $X1^{\mathrm{dom}}_{c,i}$ is the demand of industry i for domestic intermediate input c, $X2^{\mathrm{dom}}_{c,i}$ is the demand of industry i for domestic investment goods c, $X3^{\mathrm{dom}}_c, X4_c, X5^{\mathrm{dom}}_c, X6^{\mathrm{dom}}_c$ respectively are the demand of household for domestic product c, exported product c, government demand for domestic product c, and inventory demand for domestic product c. $X\mathrm{MAR}_{c,u,m}$ is the margin goods m required by all economic entities when consuming commodity c. The same applies to the import $X0\mathrm{IMP}_c$. Eqs. (17) and (18) respectively are the total supply of domestic goods and imported products equaling total demand. $P1_{c,s,i}$ and $P0_{c,s}$ are shown in Eq. (16), $X1_{c,s,i}$ is the demand of industry i for commodity c sourced from s, $\mathrm{TAX}_{c,s,i}$ is the tax revenue generated by industry i's use of commodity c sourced from s, $X\mathrm{MAR}_{c,i,m}$ is the demand of industry i for margin goods when using commodity c. Eq. (21) is the general expression of zero profit for each industry.

1.5 Model correctness test

The model tests the correctness of the calculation results by setting three conditions. First, the output value of each industry is equal to the sum of production costs (Eq. (20)). Second, the production of domestic goods is equal to the total demand for corresponding products (Eq. (21)). Third, the average value of household consumption elasticity is 1, which means that the sum of household consumption expenditure on all goods is equal to their total income (Eq. (22)).

$$V1\mathrm{PRIM}_i + V1\mathrm{OCT}_i + V1\mathrm{MAT}_i + V1\mathrm{PTX}_i = \sum_c P0\mathrm{COM}_c * Q_{c,i} \tag{20}$$

$$\sum_d \mathrm{SALE}(c, \text{“dom”}, d) = \sum_i P0\mathrm{COM}_c * Q_{c,i} \tag{21}$$

$$1 = \sum_c S3\_S_c * \mathrm{EPS}_c \tag{22}$$

where $V1\mathrm{PRIM}_i, V1\mathrm{OCT}_i, V1\mathrm{MAT}_i, V1\mathrm{PTX}_i$ are the factor cost, other cost, intermediate input cost, and production tax of industry i. $P0\mathrm{COM}_c$ is the price of commodity c. $Q_{c,i}$ is the output of commodity c produced by industry i (this model assumes that one industry corresponds to one product). $\mathrm{SALE}(c, \text{“dom”}, d)$ is the demand for commodity c produced domestically from channel d, $S3\_S_c$ is the average budget share of household consumption for commodity c, and EPS_c is the household consumption elasticity of commodity c.

1.6 Macroscopic closure block

An important part of the CGE model design is to choose an appropriate closure based on the research question. The key to setting the closure is to choose appropriate endogenous variables so that they are equal to the number of equations, thus achieving the model solution. The setting of exogenous and endogenous variables is based on the corresponding macroeconomic theory.

1.6.1 Short-run closure

Keynesian macro closure is suitable for short-run simulation. Under the condition of macroeconomic depression, labor is massively unemployed, and capital is idle. Therefore, the supply of production factors labor and capital is not restricted. Due to the existence of price stickiness, the real wage is constant in the short term, but labor can flow freely between industries, and the total employment is endogenous, determined by demand alone. The price of the factor is fixed. In the simulation, the price of the factor is exogenous, and the total demand for the factor is endogenous, without endowed restrictions.

For industries where investment is affected by the market, industry investment varies with the capital return rate. The amount of industry investment depends on the current net investment return rate of the industry, which is determined by the total return rate and depreciation, and the total return rate is determined by capital rent and investment product prices. The equation for the current investment return rate is as follows:

$$\mathrm{RORC}_i = \mathrm{GERT}_i - \mathrm{DEP}_i = \frac{P1\mathrm{CAP}_i}{P2\mathrm{TOT}_i} - \mathrm{DEP}_i \tag{23}$$

where RORC_i is the current net investment return rate of industry i, GERT_i is the total return rate, DEP_i is the depreciation rate. $P1\mathrm{CAP}_i$ is the capital rent, and $P2\mathrm{TOT}_i$ is the investment product price.

For industries where investment is not affected by the market, industry investment varies with total investment. Industries where investment is not affected by the market, such as education, public utilities (industries dominated by government activities), and so on, are subject to policy influence (such as some industries' investment is determined by policy), and industry investment in the model varies with total investment.

$$x2\text{totchange}_i = x2\text{change} \tag{24}$$

where $x2\text{totchange}_i$ is the rate of change in investment for industry i, $x2\text{change}$ is the rate of change in total investment for all industries.

1.6.2 Long-run closure

Neoclassical macro closure is suitable for long-run simulation. All prices, including factor price and commodity price, are completely elastic and determined endogenously by the model. The existing actual supply of factors such as labor and capital are fully employed. In the simulation, the price of the factor is endogenous, the factor endowment is exogenous, and there is no unemployment rate.

In the long-run closure, industry investment is affected by the market and varies with capital stock. Capital can be transformed into production capacity, so capital is variable, the return rate is constant (rent and cost change in proportion), the capital growth rate is fixed (Eq. (25)), the expected return rate of each industry is equal, and industry investment varies with the change of industry capital stock. The equation is as follows:

$$X2\text{TOT}_i = X1\text{CAP}_i \times \overline{\text{GGRO}_i} \tag{25}$$

where $X2\text{TOT}_i$ is the amount of investment of industry i, $X1\text{CAP}_i$ is the capital stock, GGRO_i is the capital growth rate.

1.7 Dynamic mechanism

The dynamic mechanism of the model mainly consists of two parts, one is the dynamic adjustment mechanism of the capital market, and another is the real wage lag adjustment mechanism in the labor market.

(1) Dynamic mechanism of capital market

The end-of-period capital is equal to the beginning-of-period capital stock minus depreciation plus the amount of new investment in the current period. To overcome the risk of capital change being too fast, we give three conditions to restrict the capital growth rate based on the positive relationship between the expected capital return rate and capital growth rate. Firstly, when the expected return rate is equal to the natural capital return rate, the capital growth rate follows the general historical pattern. When the expected return rate is particularly high (or low), the growth rate (or decline rate) of capital will not be higher than (or lower than) the maximum capital growth rate (or minimum capital decline rate) we set. The capital accumulation equation in the dynamic CGE model is as follows:

$$K_{t+1} = K_t(1-D) + I_t \tag{26}$$

$$\frac{I_t}{K_t} = \frac{K_{t+1}}{K_t} - 1 + D = \text{KGR}_t + D \tag{27}$$

$$\text{RORE}_t = \text{RORN}_t + \frac{1}{C}\ln\left(\left(\frac{\text{KGR}_t - \text{KGR\_MIN}_t}{\text{KGR\_MAX}_t - \text{KGR}_t}\right) * \left(\frac{\text{KGR\_MAX}_t - \text{TREND}_t}{\text{TREND}_t - \text{KGR\_MIN}_t}\right)\right) \tag{28}$$

where K_t is the initial capital stock, K_{t+1} is the final capital stock, I_t is the current investment amount, D is the depreciation rate, which is considered a fixed parameter. RORE_t is the expected capital return rate, RORN is the natural capital return rate. KGR is the capital growth rate, KGR_MAX (KGR_MIN) is the maximum (minimum) capital growth rate set. TREND is the historical law of capital growth. The relationship between the expected capital return rate and capital growth rate is shown in Figure 3.

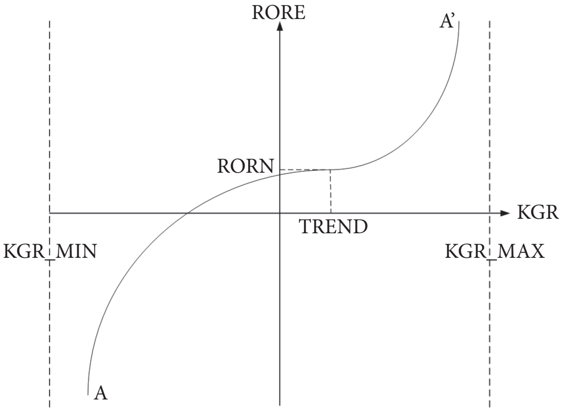


Fig. 3 Relationship between expected rates of return and capital growth.

(2) Dynamic mechanism of labor market

The treatment of labor market dynamics follows the traditional macroeconomic assumptions, that when an economy is shocked while in an equilibrium state, the real wage of labor may be sticky in the short run and not easily changed. This may cause the employment level of labor in the short run to deviate from the initial equilibrium state. However, in the long run, both workers and firms are based on the target real wage, the labor market will gradually return to a long-run equilibrium state, and the real wage of workers will also change over time, ultimately leading to full employment in the labor market. The dynamic wage adjustment mechanism allows the level of employment labor, although affected by policy shocks in the short run, to return to the baseline scenario level as the wage level is adjusted. Specifically, in the policy scenario, if employment is higher than that in the baseline scenario, the real wage will rise. The rise in real wage forces companies to reduce labor, and the decrease in employment will ultimately lead to the rise in actual wages during the previous period and the decrease in employment during current period, which will eventually cause the real wage during the current period to return to the baseline scenario. This labor self-adjustment mechanism is shown in Eq. (29).

$$\left(\frac{\text{RW}_t^{\text{P}}}{\text{RW}_t^{\text{B}}} - 1\right) = \left(\frac{\text{RW}_{t-1}^{\text{P}}}{\text{RW}_{t-1}^{\text{B}}} - 1\right) + \alpha\left(\frac{L_t^{\text{P}}}{L_t^{\text{B}}} - 1\right) \tag{29}$$

where RW is real wage, superscripts P and B respectively denote the policy scenario and baseline scenario, t is the period, L is the employment rate, α is a parameter, usually taken as 0.6. When $L_t^{\text{P}} > L_t^{\text{B}}$, $RW_t^{\text{P}} > RW_t^{\text{B}}$, and RW_t^{P} will continue to rise until $RW_t^{\text{P}} = \text{RW}_t^{\text{B}}$. In the long run, the dynamic adjustment of the capital market adjusts with changes in the labor market. As employment gradually returns to the baseline scenario, real labor wage will adjust accordingly, and the ratio of actual return on capital and labor will also change accordingly. This will prompt producers to make trade-offs between labor and capital's relative prices, thereby determining the capital-labor ratio for long-run production.

1.8 Indicator results

The model proposed in this study has extensive economic data provision capabilities, as detailed in Table 1. This model can provide researchers and decision-makers with rich economic indicators, thereby supporting in-depth economic analysis and decision-making.

Table 1 Various economic indicators

Type of indicators	Specific indicators	Dimension of indicators
Macroeconomic indicators	Employment	Industry
	Price	/
	Current capital stock	Industry
	Real wage	Industry
	Price of labor	Industry
	Price of capital	Industry
	Land use	Industry
	Price of land	Industry
	Total factor productivity	Industry
	GDP	/
Expenditure-side GDP indicator	Household consumption	Commodity × Source
	Investment demand	Commodity × Source × Industry
	Government expenditure	Commodity × Source
	Export	Commodity
	Import	Commodity
Tax indicator	Production tax	Industry
	Consumption tax	Commodity × Source × Industry × Agent
	Other taxes	Industry
	Import duty	Commodity

2 Data processing

2.1 Economic data

The economic data for the CGE model is mainly derived from input-output tables, but compared with input-output analysis, the CGE model has higher requirements for data processing. Figure 4 shows a basic framework of our model's economic database, which is mainly composed of three matrices: absorption matrix (Figure 4(a)), joint production matrix (Figure 4(b)), and import duty matrix (Figure 4(c)). We mainly refer to the database construction methods of the CGE model in China by the CoPS[18]

(a) Absorption martrix

Size	Producers (1)	Investors (2)	Household (3)	Export (4)	Government (5)	Inventories (6)
Commodities	C × S × I	C × S × I	C × S	C	C × S	C × S
Margins	C × S × I × M	C × S × I × M	C × S × M	C × M	C × S × M	C × S × M
Taxes	C × S × I	C × S × I	C × S	C	C × S	C × S
Labour	O × I					
Capital	I					
Land	I					
Production tax	I					
Other costs	I					

C = Commodities
S = Source: Domestic, Imported
I = Industries
M = Margin Commodities
O = Occupation

(b) Joint production matrix

Size	Producers
Commodities	C × I

(c) Import duty matrix

Size	Import duty
Commodities	C × I

Fig. 4 Basic framework of model economy database: (a) absorption matrix, **(b)** joint production matrix, **(c)** import duty matrix. Reproduced with permission from Ref. [20], © ZEW 2010.

and GTAP Center[19] to build our database.

The absorption matrix is the most critical data of the model, describing the input sources of production activities of various behavioral entities in the model and the use of outputs, revealing the quantitative relationships of mutual dependence and mutual restraint between various sectors of the national economy. The columns of the absorption matrix represent the input structure of production activities of various behavioral entities, including (1) production inputs of product sectors, (2) capital formation, (3) household consumption , (4) export demand, (5) government consumption, (6) and inventory changes. Rows represent destinations, where the first row represents the destination of goods. The second row represents the destination of margin services, which are the transportation cost, insurance, warehousing, and so on. Only domestically produced products can provide margin services. Wholesale and retail, transportation, warehousing, and insurance industries are generally considered to provide margin services. The third row represents the indirect tax paid by various behavioral entities for the consumption of goods. These three rows correspond to the USE matrix (the first quadrant and the second quadrant) in the input-output table. The fourth to sixth rows are the value-added inputs of product sectors, representing labor compensation, capital compensation, and land compensation, respectively, corresponding to the value-added matrix (the third quadrant) in the input-output table. The last two rows represent other costs paid by manufacturers, such as production taxes, industry subsidies, or administrative fees.

The joint production matrix describes the production of different products by various industries and is a two-dimensional matrix in which the row represents the product sector and the column represents the industry sector, indicating that an industry can produce multiple products, and each product may be produced by multiple industries. The row and column of China's input-output table are product sectors, and the production matrix constructed based on this is a diagonal matrix. The data corresponds to the total output (total input) in the input-output table. The import duty matrix accounts for the import duty of various imported goods and is a one-dimensional matrix of product dimensions. Based on the import data of goods and services and import duty data in the "China Statistical Yearbook", and China's tariff rates in the GTAP database, the import duty matrix can be derived from the import data in the input-output table.

In addition, to analyze the role of different power generation technologies and the effects of relevant power policies in responding to climate change actions, we split the power industry of the input-output table into eight different power industries based on the power generation data from the "China Statistical Yearbook" and the "China Electric Power Yearbook". These industries are coal-fired power, gas-fired power, nuclear power, hydroelectric power, wind power, solar power, biomass power, as well as transmission and distribution departments. The entire database construction work is completed using GEMPACK software[18]. After establishing each account, we check and correct the balance relationship of the database through two equations: the total input of each product sector in the absorption matrix should be equal to the total output of each product sector in the production matrix, and the total use of each product in the absorption matrix should be equal to the total supply of each product in the production matrix.

2.2 Emission data

Five types of emission accounts are designed in the database, including CO_2 generated by energy combustion and four types of environmental pollutants (SO_2, NO_x, COD, and NH_3). The input-output table provides the value of different energy products used by various economic entities, but calculating emissions requires knowledge of the physical quantities of different energy products used by various economic entities. Therefore, we need to rely on the "China Energy Statistical Yearbook" and the "China Environmental Statistical Yearbook". Matching data from different statistical calibers is a relatively difficult task. Due to data limitations, some simplified assumptions are made, which may not be consistent with actual situations. However, this is the starting point of applied research, and we hope to obtain higher-quality data over time.

In the construction of the carbon emission account, firstly, we calculate the carbon emission of different energy products by industry based on the "China Energy Statistical Yearbook" and the IPCC emission coefficient[21]. Secondly, we obtain the energy value input of different industries for energy products from the input-output table. However, these two sets of data are not consistent in terms of industry classification and energy type. The industry caliber of the "China Energy Statistical Yearbook" is coarser than that of the input-output table, and the energy types are more detailed than those of the input-output table. Therefore, it is necessary to further unify the two sets of data in terms of industry classification and energy types. Taking the latest 2017 input-output table of 149 departments as an example, we finally match the CO_2 emissions and the energy input value of 71 departments divided into five energy products, which can be used to further calculate the carbon emissions of the unit amount of energy input for different industries and energy products (carbon emission coefficient). Assuming that all sub-industries in the same major industry pay the same price for the same energy product[22, 23], the carbon emission information of 149 departments divided into energy products in the input-output table can be obtained by using the above carbon emission coefficients and the energy input matrix in the input-output table. For more specific calculation processes, please refer to the paper[24].

We take a similar approach in the construction of the environmental pollutant emission account. At present, the "China Environmental Statistical Yearbook" and the "National Pollution Source Census Bulletin" basically cover the production and emission of major pollutants from various types of pollution sources in China, and can provide SO_2, NO_x, COD, and NH_3 emission data for 42 industrial categories, agricultural pollution sources, and domestic pollution sources. The industry classification of the input-output table is more detailed than the above statistical data, so it is necessary to decompose the above data on a finer industry caliber of the input-output table. Past studies have shown that major environmental pollutants have a high degree of homology with greenhouse gases. Therefore, for both SO_2 and NO_x, we assume that the emission of each department is closely related to its fossil energy input. Under this assumption, we use the emission data provided by the statistical data as the total control, and the proportion of fossil energy input of each corresponding sub-department in the input-output table to the total fossil energy input of the corresponding major industry as the share to obtain the SO_2 and NO_x emissions of each department in the input-output table. COD and NH_3 come from production or living processes. We believe that they are closely related to the total activity level. Therefore, we use the emission data provided by the statistical data as the total control, and the proportion of output value of each corresponding sub-department in the input-output table to the total output value of the corresponding major industry as the share to obtain the wastewater discharge data of each department in the input-output table. Zhang et al. (2015) [25] provide more specific processing procedures.

2.3 Key parameters

Model parameters consist of two categories. The first category comprises parameters such as the savings rate, tax rate, marginal propensity to consume, and emission coefficient. These can be directly computed using the foundational database or model equations. The second category encompasses substitution elasticity, demand price elasticity, and expenditure elasticity. These parameters rely on empirical estimation, often constrained by data limitations and methodological choices. To circumvent inaccurate estimations that might lead to deviations in the model results, we primarily adopt the elasticity configurations from CGE models relevant to China. These widely accepted configurations serve as a benchmark for calibrating the elasticity values in our model. Table 2 lists specific values and sources of the main elasticities.

Table 2 Main elasticity values and sources

Main elasticity	Value	Sources
Armington elasticity of substitution	0.9–5.2	GTAP Tenth Edition[26]
Elasticity of household expenditure (EPS)	0.55–1.98	GTAP Tenth Edition[26]
Price elasticity of export demand	2.0	GTAP Tenth Edition[26]
Elasticity of energy-capital and labor-land substitution	0.5	Feng et al., 2021[27]
Elasticity of energy and capital substitution	0.5	Feng et al., 2021[27]
Elasticity of electric and non-electric energy substitution	2.0	Feng et al., 2021[27]
Elasticity of non-electric energy substitution	0.5	Cui et al., 2020[28]
Basic power supply and unstable power supply substitution elasticity	2.0	Wu et al., 2020, Jia et al., 2021[29, 30]
Elasticity of basic power supply substitution	4.0	Dai et al., 2011[31]
Elasticity of substitution of unstable power supply	4.0	Wu et al., 2020[30]

3 Algorithm and result explanation

3.1 Linearization algorithm

When calculating with the GEMPACK software, due to the size and complexity of the model, we need to convert the horizontal form of the equations to the linearized form and then solve them by Euler and other methods. The linearized equations can make the solution of the model faster and the results obtained by extrapolating the Euler's multi-step method are almost equal to the real values. Euler's method is to divide the change value of the variable into several intervals. The change value of the first interval is the value of the interval length multiplied by the value of the differential equation at the initial point. Similarly, after reaching the second point, the differential equation value at that point is multiplied by the length of the interval to the second change in the dependent variable, iterating repeatedly to the endpoint. The details are shown in Figure 5.

Assuming that the initial equation is shown in the AEF curve. The initial point is at point A. Euler's one-step method arrives at point C through the tangent line ABC at point A by the step $h = x_1 - x_0$, and the result obtained has a very large error with the real value of point F. The two-step method first arrives at point B through the tangent line at point A by step $h/2$ and then arrives at point D from point B through the tangent line at point E, which effectively reduces the error. The relationship of the y values before and after the two steps can be expressed by Eq. (30):

$$y^{(n+1)} = y^{(n)} + \frac{h}{N} y'(x_n) \tag{30}$$

where n denotes the total number of steps. The error of Euler's method can be obtained by Taylor expansion, as an example of one-step method.

$$y_1^{(1)} = y(x_0) + h\dot{y}(x_0) \tag{31}$$

$$\begin{aligned} e_1 = & y(x_1) - y_1^{(1)} = y(x_0) + hy'(x_0) + \frac{h2}{2} y''(x_0) + O(h^3) \\ & - (y(x_0) + hy'(x_0)) = \frac{h^2}{2} y''(x_0) + O(h^3) \end{aligned} \tag{32}$$

where $y_1^{(1)}$ is the Euler one-step solution result, x_0 and x_1 are respectively the initial and final values of the independent variables, y' is the differential equation of the initial equation, h is the length of the interval $x_1 - x_0$, e_1 is the one-step error, and $y(x_1)$ is the value of the true function y when $x = x_1$. The polynomial of $y(x_1)$ can be obtained by Taylor expansion, and finally the error value. The same can be derived for the multistep method:

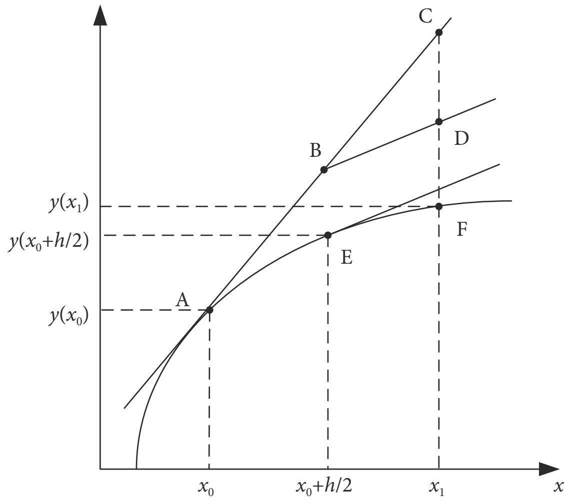


Fig. 5 Euler method solving process.

$$y^{(n)}=y\left(x_{\mathrm{n}-1}\right)+\frac{h}{n} y'\left(x_{\mathrm{n}-1}\right) \tag{33}$$

$$e^{(n)}=y\left(x_{\mathrm{n}-1}+\frac{h}{n}\right)-y^{(n)} \tag{34}$$

$$e=\sum\nolimits_{n} e^{(n)} \tag{35}$$

where $y^{(n)}$ is the solution result of the nth step in Euler's multistep method, $y\left(x_{n-1}\right)$ is the true value at the starting point of the nth step. $(h/n)y'\left(x_{n-1}\right)$ is the value of change of the dependent variable in the nth step. $e^{(n)}$ represents the error caused by the nth step, which is equal to the true value in this step minus the Euler's solution result, e is the total error. It has been verified that doubling the step size of the Eulerian method will also reduce the error by a factor of two. In addition, extrapolation is the derivation of the true solution from the error of the Eulerian solution, as described in paper[32]. If the results of Euler's one-step, two-step and four-step methods are available, the following results can be extrapolated based on the error relationship between the results of Euler's method and the true value:

$$y^{E3}=\frac{8w_3\left(4N\right)-6w_2\left(2N\right)+w_1\left(N\right)}{3} \tag{36}$$

where y^{E3} is the exact solution extrapolated from the three Euler results. $w_3\left(4N\right)$, $w_2\left(2N\right)$ and $w_1\left(N\right)$ respectively are the Euler 4-step, 2-step and 1-step results. It is verified that the error between the exact solution and the true solution of the extrapolation method is usually less than 0.00001.

3.2 Back-of-the-envelope explanations of results

Similar to other models, the internal economic framework of the CGE model in this paper can be expressed through the transmission of a set of equation variables. This set of relationships is defined as the BOTE model, which is used to briefly describe the core mechanism of internal transmission between various departments. In this section, the economic mechanism behind the long-run simulation of the impact of the carbon tax on macroeconomic operations is explained. The main equations of the BOTE model are as follows:

$$\text{Income-side GDP}:\ Y\downarrow=\overline{A}\times F_Y\left(K\downarrow,L\right) \tag{37}$$

$$\text{Expenditure-side GDP}:\ Y\downarrow=C+I\downarrow+G+\left(X-M\right)\uparrow \tag{38}$$

$$\text{Capital factor return}:\ \overline{\left(Q/P_2\right)}=\left[A\left(1/T\right)\right]\downarrow\times\left(\frac{P_{\mathrm{g}}}{P_2}\right)\times F_{\mathrm{K}}\left(K\downarrow/L\right)\uparrow \tag{39}$$

$$\text{Labor factor return}:\ \left(w/P_3\right)\downarrow=\left[A\left(1/T\right)\right]\downarrow\times\left(P_{\mathrm{g}}/P_3\right)\times F_L\left(K\downarrow/L\right)\downarrow \tag{40}$$

$$\text{Investment}:\ I\downarrow/K\downarrow=\overline{R_I} \tag{41}$$

$$\text{Export}:\ X\uparrow=F_X(P_4\downarrow) \tag{42}$$

$$\text{Income}:\ M\downarrow=F_M(Y\downarrow,ER) \tag{43}$$

$$\text{Term of trade: } P_{\mathrm{toft}}\downarrow=P_4\downarrow/P_M \tag{44}$$

$$\text{Tax structure: } T\uparrow=F_{\mathrm{T}}\left(T_{\mathrm{CO_2}}\uparrow,T_{\mathrm{C}},T_{\mathrm{P}}\right) \tag{45}$$

The meanings of each variable are shown in Table 3. Eqs. (37) and (38) are GDP calculated by income method and expenditure method. Eq. (39) indicates that the return to the capital factor is determined by a chi-square function of the amount of capital per unit of labor, F_{k}, multiplied by the inverse of technological progress, tax revenue, and the term of trade. Eq. (40) similarly explains the determinant of the return on labor. Eq. (41) indicates the assumption in the model that investment is assumed to move at a fixed ratio to the capital stock in the model. Eq. (42) indicates that export is determined by the price of export. Eq. (43) indicates that import is determined by GDP, that is, domestic demand and the real exchange rate. Eq. (44) indicates that the term of trade is equal to the ratio of export price to import price. Eq. (45) shows the main composition structure of taxes, including carbon tax, consumption tax, and production tax.

Based on the interpretation of the equations above, the following describes the economic impact mechanism of the carbon tax shock. In the model, the carbon tax is reflected as a value-added tax, which first affects the tax revenue T in Eq. (45). Since the return on capital remains unchanged in the long-run closure, that is, the left side of Eq. (39) remains unchanged, the imposition of carbon tax increases T, and the technology remains unchanged, that is, $\left[A\left(1/T\right)\right]$ decreases. Generally speaking, the change in trade conditions represented by $\left(P_g/P_2\right)$ is very small, so to keep the right side of the equation unchanged, the marginal capital productivity $F_K\left(K,L\right)$ increases. Since F_K is a decreasing function and labor L changes very little in long-run closure, and the capital stock K decreases. Similarly, the decrease in K leads to a decrease in real wages $\left(w/P_3\right)$ in Eq. (40) and a decrease in investment I in Eq. (41).

From Eqs. (42) and (43), it can be seen that export is determined by export price, and import is determined by *GDP* and the real exchange rate, where F_X is a decreasing function and F_M is an increasing function. Therefore, the imposition of carbon tax increases production cost, reduces production, causes a decrease in factor demand, and leads to a decrease in factor price,

Table 3 Meaning of variables

Variable	Meaning	Variable	Meaning
Y	Gross domestic product (GDP)	L	Labor
C	Private consumption	A	Technological progress
I	Investment	Q	Return on investment
G	Government expenditure	w	The nominal wage of labor
X	Export	$P_{\mathrm{g}}, P_2, P_3, P_4, P_{\mathrm{M}}$	GDP price, capital price, private consumption price, export price, import price
M	Import	ER	Real exchange rate
K	Capital stock	$T, T_{\mathrm{CO_2}}, T_{\mathrm{C}}, T_{\mathrm{P}}$	Total tax, carbon tax, consumption tax, production tax

which promotes a decrease in both the consumer price index (CPI) and export price P_4, and a depreciation of the real exchange rate, which is beneficial to the growth of export in Eq. (42). Import generally shows a downward trend due to the decrease in total income and the depreciation of the real exchange rate. The trade condition P_{toft} in Eq. (44) will also deteriorate as the export price decreases. The above analysis explains the impact mechanism of the carbon tax on macroeconomic operations. To verify the validity of this analysis method, the result of imposing a carbon tax of 100 yuan/ton is simulated. The overall situation is shown in Table 4. Except for the import volume, the direction of change in other variables in the BOTE analysis is consistent with the simulation result. Therefore, it is necessary to use CGE model simulation results to find the reasons. From the results of the CGE model, the imposition of a carbon tax on domestic goods has created a price advantage for certain imported products. This has led to a significant escalation in the volume of import, resulting in a modest increase in total imports.

Table 4 The comparison of results between BOTE analysis and CGE Model

Variable	BOTE analysis result	Simulation result variation	Whether consistent
GDP	↓	−1.10%	√
I	↓	−3.18%	√
CPI	↓	−1.23%	√
X	↑	0.27%	√
M	↓	0.06%	×
P_{toft}	↓	−0.07%	√
w/P_3	↓	−1.69%	√
K	↓	−3.09%	√

4 Application and discussion

The CGE model functions as a robust policy simulation tool, providing a strong foundation for extensive research. Our team has further expanded the fundamental CGE model into multiple critical domains, encompassing dynamic analyses of carbon tax and carbon trading market, thorough consideration of the energy rebound effect, diverse impacts of environmental tax and disclosure, as well as systematic exploration of carbon-neutral strategies. These enhancements augment the practical applicability of the CGE model, offering more reliable support for formulating comprehensive and effective policies.

4.1 Carbon tax revenue recycling

The “Opinions of the Central Committee of the CPC and the State Council on Carbon Dioxide Peaking and Carbon Neutrality in Full and Faithful Implementation of the New Development Philosophy” mentions the exploration of carbon reduction-related tax policies as part of perfecting the “dual carbon” fiscal and taxation policies. While China has already established some carbon reduction-related taxes or tax preferential policies, achieving the “dual carbon” goals still requires improvements in relevant policies. This includes deliberations on the imposition of carbon taxes and the establishment of a green taxation system to fully leverage carbon emission reduction effects. Carbon tax policies come with considerations on how to use the newly generated revenue, such as the government holding tax revenue to improve fiscal conditions or utilizing taxes to reduce residents’ consumption taxes, or exempt enterprise production taxes[24,33].

Liu and Lu (2015)[33] considered three carbon tax revenue recycling schemes: (1) retaining carbon tax revenue in the government budget to improve fiscal conditions, (2) keeping the government budget unchanged and using carbon tax revenue to offset resident consumption taxes, (3) maintaining the government budget and using the tax revenue to offset corporate production taxes. This research addresses the void in studies on tax revenue recycling strategies by conducting a comprehensive analysis of the effects of diverse tax revenue recycling approaches at macroeconomic and industry-specific levels. It contributes significantly to the discourse on the intricate and multi-faceted impacts of carbon tax policies.

Introduction of carbon tax. In the model, simulation of the carbon tax is primarily introduced through changes in the indirect tax rate on fossil fuel consumption. Since the carbon tax is levied based on quantity, integrating the carbon tax into the model first requires a transformation from a quantity tax to an ad valorem tax. The fundamental approach involves:

$$C \times Q \times I = (T-1) \times \text{TaxBASE} \tag{46}$$

where, the left side of Eq. (46) represents the revenue from the carbon tax in terms of a quantity tax, while the right side represents the tax revenue in terms of an ad valorem tax. The approach to introducing the carbon tax involves deriving the ad valorem tax rate from the quantity tax on the left side. In this equation, C is the carbon tax (unit: yuan/ton), an exogenous variable in the model (policy control variable), used to simulate its impact on the entire economy by altering the changes in carbon tax. Q is the corresponding carbon emissions for each industry (unit: ten thousand tons), a coefficient included in the constructed sectoral carbon emission account. TaxBASE is the tax base subjected to carbon tax collection (unit: ten thousand yuan), already embedded within the core economic CGE model. I is a price index used for homogenization checks, assumed to change synchronously with the CPI. T is represented as 1 plus the tax rate (Power Tax), signifying the increase in indirect tax rates on fossil fuel consumption due to levying the carbon tax within industries.

The tax revenue mechanism (tax neutrality) established in this study’s model involves controlling the government’s budget deficit unchanged while returning the additional carbon tax revenue to residents in the form of consumption taxes. Mechanistically, regarding the model, the carbon tax revenue is initially included in government income. Without any revenues, this results in an increase in government fiscal income. However, with tax revenues, equivalent to maintaining the government budget, the tax burden for economic entities receiving revenues (such as producers, consumers, etc.) decreases. The formula for achieving tax neutrality is as follows:

$$\mathrm{NTR} = C * Q * I + V3\mathrm{TAX} * f3\mathrm{tax} \quad (47)$$

where NTR is the variable facilitating tax neutrality. In the policy scenario, this exogenous variable is set to zero to ensure an equilibrium between the decreased revenue from consumption taxes and the increased revenue from carbon taxes. The meanings of C, I, and Q remain the same as in Eq. (46), $V3$TAX is the consumption tax, and $f3$tax is the rate of change in the consumption tax.

This study conducted simulations based on a one-time tax in a static model. However, our dynamic model captures the impact of shocks not only in the initial year but throughout the entire period. Long-term carbon taxes are more realistic. Nonetheless, a one-time carbon tax scenario aids in determining how the economic impact of carbon tax shocks will affect the economy in the current period and how this impact will evolve over time. When continuous carbon taxes are levied, the temporal repercussions of preceding carbon taxes amalgamate with the immediate impacts of the current period's carbon tax. Therefore, a one-time policy scenario assists in distinguishing between the immediate and time-related impacts of the policy. Chen (2022)[34] utilized a one-time tax approach, employing a CGE model to quantitatively analyze the effects of China's carbon tax policy on social inequality, comparing the impact of different return strategies on income equality among various income groups. Furthermore, numerous studies have extensively examined long-term carbon tax policies using CGE models. Cao et al. (2021)[35] used 8 different CGE models to simulate the effects of low, medium, and high-intensity carbon taxes on macroeconomic aspects and carbon emissions. These models incorporated various tax return mechanisms, including strategies such as reducing value-added tax, corporate income tax, government holding, and returns to household, among others. Thus, research on tax return holds significant importance for the sustainable development of the economy.

4.2 Carbon emission trading scheme (ETS)

The carbon market enables market-based pricing of carbon emissions by defining ownership of carbon emission rights and facilitating their trade among emitters, thereby internalizing the external costs associated with emissions in industrial production[36, 37]. In comparison to the carbon tax, the ETS offers greater flexibility and potential market dynamics to drive emission reductions. Liu et al. (2013)[38] utilized the China multi-regional general equilibrium model (TermCo2) to simulate the cost of emissions reductions and economic impacts in Guangdong and Hubei provinces when implementing individual emission reductions and conducting inter-provincial carbon ETS. This study is the first to quantitatively analyze the impact of implementing interregional carbon trading markets at the regional level. Furthermore, simulations were conducted to assess the impacts of the carbon trading market within individual regions, encompassing Hubei Province[39], Tianjin Municipality[4], and South Korea[40].

To derive the shadow price (P) of carbon allowances — representing the price resulting from the overall restriction on carbon emissions within a specific region during a defined period, the CGE model introduces the concept of a carbon emission control upper limit (Q). As depicted in Figure 6, simulating a set of upper limits on total carbon emissions allows for the derivation of the marginal abatement cost (MAC) curve. The more stringent the total emission restrictions, the higher the marginal abatement costs, consequently resulting in higher allowance prices.

Carbon ETS usually covers several industries, each facing varying degrees of quota constraints. Additionally, due to differences in carbon emission structures and mitigation potentials among different industries, their respective marginal abatement cost (MAC) curves also differ. Therefore, in the absence of quota trading, the MAC for different industries is also inconsistent. As shown in Figure 7, assuming the existence of Industry 1 and Industry 2, each obtaining carbon quotas Q_1 and Q_2, the CGE model can simulate the MAC curves for these two industries. When there is no quota trading, the MACs for

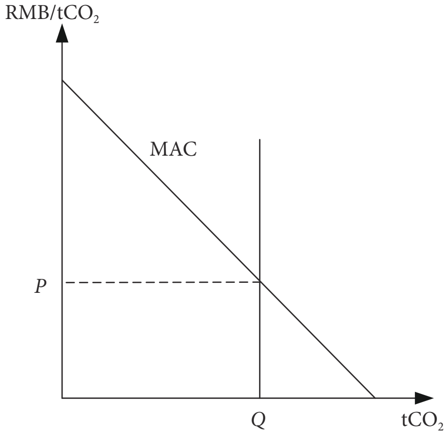
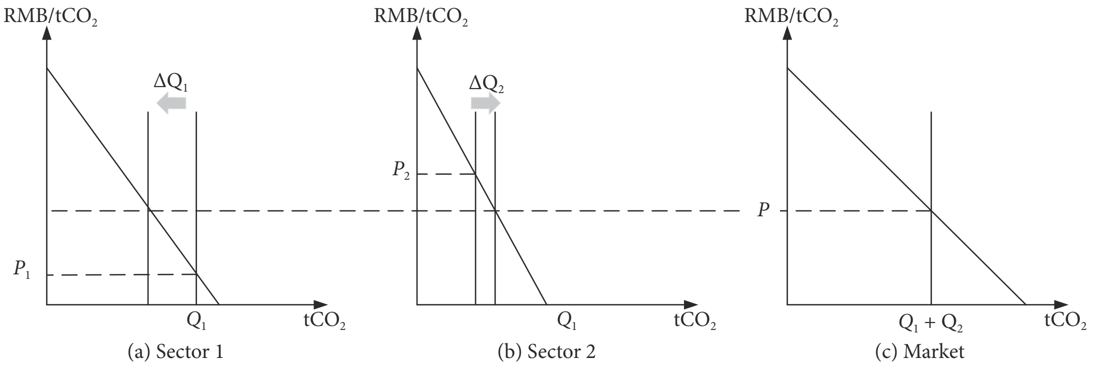


Fig. 6 MAC curves in the CGE model.



(a) Sector 1 (b) Sector 2 (c) Market

Fig. 7 Mechanism of the carbon trading market.

Industry 1 and Industry 2 are represented as P_1 and P_2, respectively. Upon allowing quota trading (ΔQ) between Industry 1 and Industry 2 until the quota price P equals their respective MACs, the CGE model can simulate the impact of the ETS on different industries, considering the inter-industry influences, thereby obtaining a composite MAC curve covering all industries involved.

The solution to the equilibrium carbon price in ETS can be expressed as

$$\min\sum_i C_i = \sum_i \left[\sum_n (X_{ni} \times Pe_n + E_i \times P)\right] \tag{48}$$

$$\text{s.t.} \sum_i Q_i = \sum_i E_i \tag{49}$$

where C_i is the energy input cost for industry i. E_i is the emissions of industry i. X_{ni} is the consumption of fossil energy n by industry i. Pe_n is the price of energy n, P is the equilibrium carbon price. Q_i is the carbon emission control upper limit for industry i. In this way, the CGE model can endogenously determine the equilibrium price P, ensuring the clearance of the carbon market.

Currently, quantitative simulation analyses regarding the national ETS mainly involve the scope of industries covered by the carbon market. These studies can be broadly categorized into three types: single-industry coverage[41, 42], coverage of all high-energy consumption industries[43, 44], and coverage of all industries[45]. Furthermore, several studies further delve into examining the impact of different initial carbon quota allocation methods on carbon abatement costs across various industries[44, 46]. Other research efforts aim to explore the coordination between carbon trading and carbon tax mechanisms, consistently concluding that their integration can achieve better emission reduction outcomes and economic performance[47, 48]. Hence, in-depth research into carbon trading mechanisms contributes to fully leveraging the power of market mechanisms and more effectively driving down the costs associated with emission reductions.

4.3 Energy efficiency rebound effect

The energy efficiency rebound originated from research on the "Jevons Paradox" [49–51], this paradox refers to the phenomenon where technological advancement leads to an increase in resource consumption despite an improvement in resource efficiency. The study categorizes rebound effects into three types: direct rebound, indirect rebound, and the economy-wide rebound[52–54]. Wei and Liu (2017)[55] considered direct and indirect rebounds are considered as changes in industrial-level energy consumption, unaffected by other industries and market prices. The economy-wide rebound reflects all adjustments made by the entire economic system in response to localized energy efficiency improvements, ultimately impacting the final energy-saving outcomes.

Lu et al. (2017)[56] simulated the impact of rebound effects at both the production and overall economic levels when the efficiency of five energy sources of coal, oil and gas, refined oil, electricity, and gas was increased by 5% with a CGE model. The marginal contribution of this study lies in its comparative analysis of the rebound effects on energy consumption due to efficiency improvements in different energy sources, highlighting the disparities between the production and consumption sides. Zhou et al. (2018)[57] further analyzed the primary sources of rebound effects based on this foundation. The study's marginal contribution is its detailed breakdown of specific energy products causing energy consumption rebound. This approach enhances the study of rebound effects in energy consumption by providing a more sophisticated analysis. The measurement of rebound effects referenced Koesler et al. (2014)[58]:

$$R = \left(1 + \frac{\dot{E}}{\alpha\gamma}\right) \times 100 \tag{50}$$

where R is the economy-wide rebound. $\dot{E}$ is the rate of change in energy use for the entire economy following a series of adjustments. α is the share of energy consumption from the individual p where the energy efficiency improvement occurs in relation to the total energy consumption, E_p/E, p is the producers, including $j = 1, \cdots, 159$ production sectors. γ is the extent of energy efficiency improvement. If $R = 0$, there is no rebound effect, if R = 20%, 20% of the expected energy savings are offset by rebound mechanisms. Backfire occurs when $R > 1$.

Energy consumption E is composed of all industries (j), households (H), government (G), investment (I), exports (EX) and inventories (S):

$$\Delta E = \sum_j \Delta E_j + \Delta E_{\mathrm{C}} = \sum_j z_j E_j + \Delta E_{\mathrm{H}} + \Delta E_{\mathrm{G}} + \Delta E_{\mathrm{I}} + \Delta E_{\mathrm{EX}} + \Delta E_{\mathrm{S}} \tag{51}$$

where z_j is the percentage change in energy consumption for industry j.

According to Eq. (50) and Eq. (51), we can obtain the economy-wide rebound effect can be decomposed as follows:

$$R = \left(\sum_j R_j' \times 100\right) + \left(\frac{\Delta E_{\mathrm{H}}}{\gamma E_{\mathrm{P}}} + \frac{\Delta E_{\mathrm{G}}}{\gamma E_{\mathrm{P}}} + \frac{\Delta E_{\mathrm{I}}}{\gamma E_{\mathrm{P}}} + \frac{\Delta E_{\mathrm{EX}}}{\gamma E_{\mathrm{P}}} + \frac{\Delta E_{\mathrm{S}}}{\gamma E_{\mathrm{P}}}\right) \times 100,$$

$$\text{where } R_j' = \left(1 + \frac{z_j}{\gamma}\right) \times \frac{E_j}{E_{\mathrm{P}}} \tag{52}$$

where $R_j' = (1 + z_j/\gamma) \times (E_j/E_{\mathrm{P}})$, represents the rebound effect weight for industry j.

Referring to Saunders (2013)[59], the industry rebound effect can be further decomposed into output effects and substitution effects. Based on the CES function using algorithmic linearization[32], the demand equation for energy input in industry j is as follows:

$$z_{ij} + \gamma_{ij} = x_j - \delta_j \left[\left(p_{ij} - \gamma_{ij}\right) - \sum\nolimits_i S_{ij} * \left(p_{ij} - \gamma_{ij}\right)\right] \tag{53}$$

where z_{ij} is the use of energy i in industry j. γ_{ij} is the energy efficiency of industry j in using energy i. x_j is the output of industry j, p_{ij} is the price of industry j using energy i, p_j is the average production cost of industry j. σ_j is the elasticity of substitution for energy use in industry j, and S_{ij} is the cost share of energy i in the total energy input of sector j. According to R_j' and Eq. (53), the industry rebound effect can be decomposed. See Zhou et al. (2018)[57] for details.

Many research findings indicate that individual behavior changes are mainly at the family level, which is a source of rebound effects. In this case, final consumers decide to use more energy by adopting more energy-efficient technologies, partially offsetting the impact of efficiency improvements on energy consumption[57, 60]. The achievement of future carbon reduction goals is highly likely to bring about rebound effects in energy consumption, revealing the macroeconomic aspects of the energy rebound effect are important for the world to reduce energy consumption and curb greenhouse gas emissions[61]. Furthermore, the application of emerging emission reduction technologies such as carbon capture and storage (CCS), hydrogen energy, and energy storage could potentially cause rebound effects in energy consumption. Hu and Wu's (2023)[62] research shows that deploying CCS technology leads to a decrease in net emissions but results in higher total emissions, particularly in coal emissions, compared to scenarios not considering CCS technology. Therefore, it is necessary to balance the consideration of technological progress and the application of emission reduction effects and potential rebound effects to optimize economic impacts.

4.4 Environment analysis

The Environmental Protection Tax Law was officially implemented in China on January 1, 2018. Many studies conducted extensive discussions on the environmental tax around that time. Before the formal implementation of the environmental tax, Liu et al. (2017)[63] assessed the economic and environmental impacts of thermal power plants investing in desulfurization and denitrification equipment to reduce pollutant emissions and comply with new emission standards. Afterward, Liu et al. (2017)[64] conducted a comparative analysis of three scenarios for all industries: individual taxation for SO_2, individual taxation for NO_x, and simultaneous taxation for both SO_2 and NO_x. Similar to the decomposition of rebound effects, Liu et al. (2017)[65] further decomposed the emission reduction caused by the environmental tax into five types: total output effect, process emission effect, intermediate input substitution effect, energy substitution effect, and domestic and foreign product substitution effect. Hu et al. (2018)[66] specifically focused on the impact of returning environmental taxes to residents at different proportions (through consumer tax reductions) while discussing the decomposition of emission reductions due to environmental taxes. This series of studies has provided an in-depth and comprehensive analysis for understanding the impact mechanisms before and after the implementation of environmental taxes.

However, the extensive implementation of environmental taxes has exposed certain limitations. As a formal means of environmental regulation, environmental taxes involve relatively high regulatory costs and inflexible tax rates that cannot promptly adjust to environmental changes and new technological applications. Conversely, environmental information disclosure (EID) serves as an informal regulatory mechanism with greater flexibility, wider participation, and diverse formats. It motivates enterprises to disclose information on pollutant emissions, environmental investments, and planning. This leverages the supervisory role of non-governmental organizations over businesses, compensating for governmental shortcomings in enforcing environmental tax laws. Zhang et al. (2022)[25] and Liu et al. (2023)[67] utilized CGE models to simulate the economic and emission impacts resulting from enhanced EID quality, focusing on energy efficiency improvements, process emission coefficients, and financing costs. This research reveals and evaluates the effects of enhanced environmental information disclosure (EID) quality on industrial output and pollutant emissions. Additionally, it illuminates the regulatory role of informal environmental controls in relation to formal environmental regulations, elucidating their underlying mechanisms and pathways. The subsequent section elucidates the incorporation of environmental taxes and EID into CGE models:

(1) Environmental tax

Before simulating the impact of environmental taxes, it is necessary to determine its scope, tax targets, and tax rates. For instance, exemptions for taxing residents, the portion of agricultural production that does not exceed emission standards is exempted, and varying tax rates across provinces are some factors that need consideration. In the CGE model, there is a need to convert the quantity tax into the ad valorem tax:

$$T_p \times E_{p,i,s} = \mathrm{BT}_p \times t_{p,i} \tag{54}$$

where T_p is the quantity tax value of pollutant p (RMB/ton). $E_{p,i,s}$ is the emission quantity (in tons) of pollutant p emitted by source s in industry i. BT_p is the ad valorem tax base of pollutant p. $t_{p,i}$ is the ad valorem tax of pollutant p levied on industry i.

(2) Environmental information disclosure

EID quality improvement mainly affects the production and emission behavior of enterprises through two paths: Firstly, improving the quality of EID can enhance a enterprise's environmental image, thereby motivating them to improve energy efficiency or specific production processes by increasing environmental investments, thereby reducing the emissions of waste water and exhaust gas. Secondly, improving the quality of EID will decrease financing costs, increase the investment and capital stock of enterprises, subsequently reducing capital prices, driving industry output expansion, and increasing emissions. According to researches[68, 69], with the improvement in EID quality, the emission intensity of SO_2 and wastewater decreases, and also a decrease in financing costs. The reduction in emission intensity is reflected in emission coefficients. The decline in financing costs is reflected by the functional relationship between capital growth and the current rate of return. Capital growth can be computed through investment and depreciation, and the corresponding current rate of return will also be determined. There exists a positive correlation between the current rate of return and the price of capital goods. When the current rate of return declines, this change ultimately reflects in the decrease of the capital goods' price. The reduction in the current rate of return is reflected in the decline in the price of capital goods. The specific formula for how financing costs affect capital is as follows:

$$\mathrm{KGR} = \frac{1}{G * \beta} * [R * (\mathrm{RORC} + \mathrm{fRORC})] \tag{55}$$

where KGR is capital growth rate, similar to the previous statement. RORC is the current rate of return. We refer to the ORANIG model[14, 16] for the parameters $G = 0.3, \beta = 10, R = 2$. The exogenous variable fRORC is added to characterize the change in the financing cost in the short run. If the financing cost decreases, fRORC > 0, whereas if the financing cost increases, fRORC < 0.

The main reason for adopting a long-term closed mechanism in the study is to enhance the quality of EID by raising the cost of capital funds to stimulate increased investment. However, only through long-term incremental investments can be transformed into the accumulation of capital stock.

Tax policies have played a significant role in pollution reduction and carbon emissions, yet there are still many areas worthy of further study. Financial instruments have broad application prospects and development space in promoting pollution reduction and carbon mitigation. According to policy regulations, the future proportion of green credit may reach 60% or 90%. China's green credit policy is expected to have profound implications for energy structure, carbon emissions, industry, and macroeconomics[70, 71]. Therefore, how to accurately introduce green financial mechanisms into CGE models and simulate the impact of various mechanisms is an issue worthy of in-depth discussion.

4.5 Carbon neutrality

The proposal of the "dual carbon" goals has triggered multifaceted considerations. In fact, assessing the impacts of carbon reduction policies should encompass the interplay between policies, which could result in trade-offs and synergies. Trade-offs and synergies between policies might either weaken or strengthen their effects. Neglecting these interactions might lead to an overestimation of policy effectiveness or an underestimation of economic costs. Liu et al. (2022)[72] selected carbon pricing policy, renewable energy policy, energy efficiency improvement, and electricity substitution policy after reviewing prominent domestic and international carbon neutrality policies. The study aims to address the lack of understanding regarding the effectiveness, trade-offs, and synergies among policies in achieving China's dual carbon goals. It evaluates the mitigation effect, economic cost, and efficiency (GDP loss per unit of carbon reduction) of these policies and investment portfolios. Furthermore, it quantifies the trade-offs and synergies among the mitigation policies.

We have considered the four policies in detail, with the carbon pricing policy mentioned above and the cost-neutrality principle of the other three introduced below: (1) The national policies aim at reducing the cost of renewable energy sources, correspondingly increasing the costs of fossil fuels. Moreover, fossil fuel industries are actively exploring breakthroughs in new energy technologies to facilitate a green transition. Consequently, the cost of renewable energy development mainly comes from squeezing development funds from the fossil energy sector. The economic cost of the decline in renewable energy costs by leveraging the rise in fossil fuel expenses[73–75]. (2) The cost of energy efficiency improvement comes from investments in technological R&D of production factors such as labor and capital[76, 77]. (3) Electrification includes both supply-side and demand-side initiatives[78–80]. Given that supply-side electrification measures have been considered in renewable energy policies, within the electricity substitution policy, we only consider demand-side electrification transformations. In this policy, the impact of a preference for electricity is assumed to be energy-neutral. that is, if the end sector uses more electricity, there is a decrease in the use of fossil fuels. Therefore, changes in energy preferences do not affect the total energy demand of users[81, 82].

In the future, carbon neutral research will continue to be the focus of the CGE model simulation field. Our team is still actively engaged in research in this field and has many ongoing research projects and comprehensive considerations. In terms of model improvement, the introduction of disruptive abatement technologies will improve the accuracy of abatement pathway simulations. Among them, the introduction of emission reduction technologies such as CCS, energy storage technology, and hydrogen energy (green, blue, and gray hydrogen) can be considered, and large-scale coal power decommissioning around 2035 is expected to be an important modeling improvement point. Meanwhile, further research can be conducted on multi-objective synergistic target setting as well as the introduction of an uncertainty mechanism to highlight technical support and technological breakthroughs in policy measures. In terms of policy scenario design, consideration can be given to adding the influencing factors of carbon finance policies, comprehensively considering the feasibility of policy combinations, studying the differences in the quantity and contribution of policy combinations in different periods, optimizing the time dimension of policy combinations and intensities, making the optimal policy choices between global and local, and studying in depth the interrelationships between different policies of the shocks. These directions for model improvement and policy scenario design are expected to provide a more comprehensive and in-depth perspective for carbon neutral research.

In summary, utilizing the CGE model facilitates a profound exploration of the comprehensive impact of carbon neutrality policies on the economy, environment, and society. This all-encompassing assessment provides policymakers with a more thorough understanding, formulating policies more informedly. Reasonably designing policies in the model to achieve a balance between emission reduction costs and economic growth, and ensure sustainable development, is one of the key issues and has important guiding significance for policymakers.

5 Conclusions

This article provides a detailed description of the CGE model developed by our team. The model integrates fundamental economic modules with energy and environmental components, encompassing extensive data on energy consumption, emissions, and pollutants. It offers a comprehensive outline of the model construction process, intended as a reference for readers and model developers. The construction of the model fully considers the selection of various forms of CES functions in the production process, utilizes different closure mechanisms for different time scales, and provides flexible investment decision-making mechanisms for different research objectives. In the application of the CGE model, we emphasize the significance of the mechanism's rationality and the time scale. Selection of these aspects is critical to ensuring the scientific validity of the research and in offering effective policy recommendations.

While the CGE model incorporates certain assumptions and simplifications, it retains significant value as a policy-guiding tool. Although it cannot accurately quantify real-world results, it can provide crucial economic indicators and trends in production activities. By simulating different policy scenarios, provides valuable references for decision-makers. Our team has conducted research on the carbon tax mechanism, carbon market trading, rebound effect from improved energy efficiency, environmental tax, EID, carbon neutrality, among other areas. In addition, CGE model can be applied across multiple research fields such as economic growth, societal issues (e.g., poverty and inequality), as well as various energy and environmental concerns. The scalability and versatility of the CGE model make it an essential tool for addressing numerous economic challenges, offering robust support for exploring and resolving these issues.

However, our model still has some limitations. Firstly, in terms of model setting, the model remains a single-region model following the assumption of a large country, and it is recommended to use the global GTAP model when analyzing issues in international trade. Secondly, in the model theory, the LES consumption function does not consider the factor of residents using the balance after basic consumption expenditure for savings or investments. Moreover, the total budget is the sum of expenditure for demand on all goods, which is an endogenous variable and cannot be exogenous, thus rendering the model difficult to estimate. The adoption of Constant Differences of Elasticities (CDE) functions could address this, allowing for elasticity estimation in individual product consumption and price elasticity, which is more consistent with the actual situation. If you have experience or guidance in the development and application of CGE models, we sincerely welcome your valuable suggestions and assistance.

Acknowledgments

The paper is supported by National Natural Science Foundation of China (72125010, 72243011, 71974186, 72104014) and The Fundamental Research Funds for the Central Universities in Peking University.

Declaration of competing interest

The authors have no competing interests to declare that are relevant to the content of this article.

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