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Article

Research on the Collaborative Pollution Reduction Effect of Carbon Tax Policies

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Abstract: This study builds a Computable General Equilibrium model to investigate the synergistic effects and simulate the co-benefits of carbon tax policies. The conclusions are as follows: After implementing a carbon tax policy, when the carbon tax increases from 30 CNY/ton to 130 CNY/ton, and the reduction in CO_2 emissions increases from 1.223 billion tons to 3.943 billion tons. At the same time, the reduction in SO_2 emissions rises from 326,200 tons to 1,052,200 tons. However, overall, the reduction rate of SO_2 is around 88.87% of the CO_2 reduction rate. Thus, a carbon tax is also an effective policy pathway for synergistic pollution reduction and carbon mitigation. In terms of industry output, among the 15 industries, sectors such as electricity generation, aviation, and tertiary industries have increased their output, with the electricity sector achieving the highest increase of 2.9816%. Other industries have exhibited varying degrees of decline, especially coal, natural gas, oil, nonferrous metals, chemicals, steel, and building materials, with the coal industry output decreasing the most, by −49.4924%. Regarding energy consumption, as the carbon tax increases, the consumption of coal, oil, and natural gas all show a downward trend, with coal experiencing the largest decrease, at −49.5640%.

Keywords: carbon tax; reduce pollution and carbon emissions; synergistic effects; policy evaluation

1. Introduction

Air pollution and climate change are both major environmental issues facing China, and their impact on China's economic and social development is becoming increasingly profound [1,2]. For a long time, due to significant differences in the spatiotemporal scope and mode of impact and an insufficient understanding of their correlation, China's governance of the two has always been managed separately by the environmental protection department and the development and reform department. With the advancement of the relevant governance work, the mechanism of divide and rule has gradually exposed a series of drawbacks of policy overlap and even mutual constraints, thus forming a significant demand for innovation in corresponding governance mechanisms. In 2018, the State Council carried out institutional reforms to unify the responsibilities of climate change governance with the Ministry of Ecology and Environment. Subsequently, the Ministry of Ecology and Environment clarified the strategic goal of collaborative governance regarding air pollution and climate change. Is it possible to carry out collaborative governance on these two issues? What policy mechanisms should be established to ensure the achievement of strategic goals? This is a common concern among the political, academic, and industry sectors. In fact, there are countless connections between the two. Firstly, the main sources of emissions of atmospheric pollutants and greenhouse gases are the same, both coming from the large-scale utilization of fossil fuels in the process of economic growth. Secondly, some governance policies jointly regulate certain industries (such as ultra-low emissions and carbon markets that jointly regulate the power industry), while some industries also emit atmospheric pollutants and greenhouse gases (such as steel, cement, and transportation). The above connections provide a feasible and theoretical basis for collaborative governance.

China has not yet implemented a carbon tax policy, but scholars are actively exploring and studying the feasibility and impact of implementing a carbon tax in China. Carbon

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tax policy is a major policy tool for climate change governance, aiming to reduce carbon emissions and encourage a low-carbon economy. The carbon tax policy is to reduce carbon emissions by imposing taxes on carbon emitters, and its economic principle is the Pigou tax theory. The carbon tax policy needs to ensure transparency in the collection and use of taxes. The carbon tax policy imposes taxes on carbon emitters, and the government can reflect the cost of environmental pollution in prices to encourage consumers and businesses to adopt low-carbon behavior. In addition, carbon tax policies can help the government raise funds for funding and investment in environmental protection and climate change-related projects. A comprehensive review of the existing literature reveals that, in the context of China's advocacy for synergistic pollution reduction and carbon mitigation, studies have solely focused on the carbon reduction effects of carbon tax regimes and have neglected their pollution reduction impacts. Additionally, there is a lack of research examining the effects of implementing a carbon tax system on a national scale. Therefore, in the context of China's "dual carbon" strategic goals, the synergistic enhancement of pollution reduction and carbon mitigation has become the focus of environmental governance. Questions such as whether carbon tax policies can achieve synergistic effects in reducing pollution and carbon emissions, the extent of the combined emission reductions, and the impact on the economy, energy, and social welfare are crucial. Answering these questions holds significance in guiding China in realizing the "dual carbon" strategic objectives and formulating policies that synergize pollution reduction and carbon mitigation.

Based on this, the present study, addressing the urgent environmental issues of air pollution and climate change, takes the carbon tax system as a point of entry. Starting from a national perspective, by constructing a Computable General Equilibrium (CGE) model with environmental accounting and policy modules, this study aims to simulate the synergistic pollution reduction effects of carbon tax policies and their impacts on the economy, energy, and social welfare. The intention is to provide an empirical foundation for the policy design and implementation of China's "dual carbon" strategic goals.

2. Literature Review

Among the numerous climate protection policies, carbon taxes are widely advocated as the most cost-effective emission reduction measure [3]. European countries such as Sweden, Norway, the Netherlands, Denmark, Finland, and Italy have started imposing carbon taxes based on the carbon content of energy products. Research on the emission reduction effect of carbon tax and its impact on the economy has been ongoing since the end of the 20th century in foreign countries, and research on carbon tax in China has gradually emerged in recent years. Firstly, scholars discussed the feasibility of imposing a carbon tax in China, and most scholars [4–7] supported the introduction of a carbon tax. Subsequently, scholars began to study the design of China's carbon tax system and the experience summary and reference of foreign carbon tax implementation [8–11]. In addition, more scholars are starting from a quantitative research perspective, empirically simulating the various impacts and carbon reduction effects of implementing a carbon tax in China.

The research results can be divided into two aspects. Firstly, it is believed that China's implementation of a carbon tax system can achieve carbon emission reduction goals and that it has a relatively small impact on the economy. He et al. (2002) [12] established a CGE model for studying environmental issues in China. The static model was used to analyze the impact of carbon tax collection on various aspects of the national economy. The results indicate that the carbon tax has little impact on GDP and leads to a decrease in energy consumption in all sectors. The results of Wang et al. (2005) [13] indicate that when the emission reduction rate is 0–40%, the GDP loss rate is between 0–3.9%, and the marginal social cost of emission reduction is about twice the marginal technological cost. Liu et al. (2006) [14] studied the impact of imposing a carbon tax on the technological composition, electricity prices, and environmental emissions of China's power sector. The results showed that when the carbon tax reached USD 25/tC, the combined impact on the power production and consumption sides would significantly reduce the emissions of carbon dioxide, sulfur dioxide, and nitrogen oxides in the power sector, and the technological composition would also be significantly improved. Zhou et al. (2011) [15] believed that imposing a carbon tax of 30, 60, and 90 CNY/t of CO_2 would result in emission reduction rates of 5.56%, 10.45%, and 14.74% in 2020, and GDP loss rates of 0.04%, 0.10%, and 0.18%, respectively. The emission reductions that can be achieved by imposing a carbon tax are equivalent to 9.9%, 18.6%, and 26.2% of the emission reductions required to achieve the 2020 CO_2 emission intensity reduction target of 40% compared to 2005. Returning the income obtained from carbon tax to enterprises and residents can to some extent alleviate the negative impact on enterprises and residents. Zhu et al. (2010) [16] analyzed the emission reduction effects of carbon tax policies and their impact on macroeconomic and various industrial sectors by introducing six scenarios of carbon tax. The results showed that the imposition of a carbon tax can effectively reduce CO_2 emissions. Under high tax rates, compared to not imposing a carbon tax, emissions can be reduced by 11.41–21.32 million tons, and the total output and domestic product supply increases instead of decreasing. Yang et al. (2011) [17] studied the optimal carbon tax and environmental benefits under different constraint conditions, and the results showed that, under the first set of constraint conditions, the optimal carbon tax quota tax rate that should be selected is 8.84 CNY/ton. By imposing this tax rate, an environmental benefit of 3.92% CO_2 reduction can be obtained, but the economic cost of a total output decrease of 0.99% and a CPI increase of 2.96% is required. Under the second set of constraints, the optimal carbon tax rate that should be selected is 17.99 CNY/ton. By imposing this tax rate, an environmental benefit of 7.67% CO_2 reduction can be obtained, but the economic cost of a 1.96% decrease in total output and a 5.99% increase in CPI is required. The research by Liu and Li (2011) [18] shows that imposing a carbon tax can improve the energy output efficiency, reduce the use of energy factors, and reduce CO_2 emissions. Therefore, the introduction of a carbon tax has a significant energy-saving and emission reduction effect, and can effectively adjust the income distribution between factors. Wang et al. (2012) [19] used a panel data analysis model to compare and analyze the impact of carbon tax policies implemented by 31 European countries that levy carbon taxes on carbon emissions. The results indicate that the implementation of a carbon tax is conducive to carbon reduction, and the implementation of a carbon tax has not affected economic development. The simulation results of Wang et al. (2014) [20] show that imposing a carbon tax is a feasible policy choice and has a significant inhibitory effect on greenhouse gas emissions. Zhang et al. (2015) [21] constructed a computable general equilibrium model to simulate the impact of carbon tax policies on Beijing's socio-economic development. The empirical results show that the carbon tax policy has a significant energy-saving and emission reduction effect, which has a significant inhibitory effect on the output of fossil-energy-intensive industries, but has a promoting effect on the output of industries such as clean energy and service industries. The research conclusion of Lou (2014) [22] suggests that imposing a carbon tax on energy consumption, while reducing resident income tax rates and maintaining government revenue neutrality, can achieve a reduction in carbon dioxide emissions while increasing social welfare levels, thus achieving the "double dividend" effect of carbon tax. Tan and Sun (2019) [23] used the Dynamic Stochastic General Equilibrium Model (DSGE) to analyze the impact of carbon taxes on carbon reduction rates and the total output, and found that carbon taxes have medium to long-term effects on carbon reduction and environmental quality improvement. Tang et al. (2020) [24] believe that the implementation of carbon tax policies has significantly reduced energy consumption in high-carbon-emission industries and increased the use of clean energy, while the total reduction in carbon dioxide emissions has gradually increased with the increasing tax rate. Lu and Lei (2023) [25] found that imposing a carbon tax may have a negative impact on the economy, but this is generally controllable and can effectively reduce energy consumption and the total carbon emissions. Xu (2023) [26] found through simulating the impact of implementing carbon tax policies in Hainan Province that carbon tax collection reduces fossil energy consumption, accelerates enterprise transformation and upgrading, and reduces carbon emissions in various industries.

The second is that the research results pay more attention to the negative effects of carbon taxes. According to the research by Gao Pengfei and Chen (2002) [27], imposing a carbon tax will lead to significant losses in GDP. Guo et al. (2014) [28] conducted empirical research to analyze the impact of carbon tax policies on economic growth, energy consumption, and income distribution in 29 provinces, municipalities, and autonomous regions in China, as well as regional differences in their effects. The results show that the collection of carbon taxes in most regions of China will increase the inequality of social income distribution, and that the carbon tax policy has had a certain inhibitory effect on China's economic growth. Weng et al. (2021) [29] found that imposing industry-differentiated carbon taxes will have a certain negative impact on the macro economy. Lu et al. (2022) [30] studied the effectiveness of implementing carbon tax in Jiangsu Province and found that carbon tax is levied at a fixed tax rate. When the tax rate is too low, Jiangsu Province cannot achieve the goal of "carbon peaking and carbon neutrality" on schedule. When the tax rate is too high, it will have a significant negative impact on economic and social development, and the effectiveness of carbon reduction policies related to carbon tax will continue to decline over time.

In the evaluation of the effectiveness of carbon tax implementation, the methods used can be divided into three categories: the first type is econometric methods, which mostly use panel models to examine the relationship between carbon tax and economic growth [18,31,32]. The second type is numerical simulation methods, with more common ones including the CGE model [33–35] and the system dynamics model [36], and MARKAL MACRO model [25], etc., with mathematical methods established to jointly simulate and evaluate the effectiveness and impact of carbon tax systems. The third type of method evaluates the effectiveness of carbon tax policies by designing an indicator system, and then studies the emission reduction effect of the system [37]. Comparing the three research methods, indicator evaluation and its interpretation may be subjective to some extent, while econometric methods cannot overcome problems such as endogeneity and arbitrary variable selection [38]. Therefore, using more rigorous numerical simulation methods to verify the effectiveness and impact of carbon tax policies is a more appropriate economic method.

The impact of sources and social welfare is expected to provide an empirical basis for the policy design and implementation of China's "dual carbon" strategic goals.

3. Carbon Tax Policy and Its Design Elements

3.1. Development and Application of Carbon Tax Policy

Carbon tax policy is an important means of addressing climate change, and its development process mainly includes the following stages: The early exploration stage (1990s early–2000s): early carbon tax policies mainly appeared in Nordic countries such as Sweden and Finland. In 1991, Sweden became the first country in the world to introduce a carbon tax, with the main purpose of reducing carbon dioxide emissions and promoting the development of clean energy. In the following years, other Nordic countries have also introduced similar carbon tax policies. The promotion and adjustment stage (mid-2000s to 2010s): with the gradual promotion of carbon tax policies and the accumulation of practical experience, some countries began to adjust and improve carbon tax policies. For example, Norway expanded its carbon tax to include all greenhouse gas emissions in 2005 and gradually increased the tax rate. Switzerland, the United Kingdom, and Canada also introduced carbon tax policies one after another. The Globalization and Coordination Phase (2010s–present): with the increasingly severe issue of global climate change, more and more countries are considering introducing carbon tax policies. In 2015, the Paris Agreement under the United Nations Framework Convention on Climate Change was reached, and carbon tax policies received global attention. More than 40 countries around the world have implemented carbon tax policies to varying degrees. Overall, the development process of carbon tax policies has gone from the early exploration stage to the current global promotion and coordination stage, gradually becoming one of the important means to address climate change.

China has not yet implemented a carbon tax policy, but scholars are actively exploring and studying the feasibility and impact of implementing a carbon tax in China.

3.2. Design Elements of Carbon Tax Policy

Carbon tax can be levied on enterprises, industries, or individuals, and is usually calculated on a per ton basis. The design elements include the following: (1) Tax rate: The tax rate of carbon tax is the core element in policy design. The tax rate should be high enough to provide sufficient economic incentives for reducing carbon emissions, but not so high as to produce an excessive burden on the economy. The formulation of tax rates can be based on benchmark prices or price setting rules. (2) Scope of collection: Carbon taxes can be levied according to different needs, including production, consumption, or emission sources. The selection of the expropriation scope will be influenced by economic and political factors. (3) Tax purpose: The purpose of carbon tax revenue is also one of the design elements. Taxation can be used to fund renewable energy projects, improve energy efficiency, and implement other emission reduction measures, or can be used as a tax reduction or subsidy allocated to low-income groups. (4) Tax application methods: Carbon tax can be applied in different ways. For example, it can be directly levied on emission sources or be collected through various links in the energy supply chain. (5) Tax elasticity: The flexibility of carbon tax is an important design element. Policies can set tiered tax rates to encourage lower carbon emissions or higher energy efficiency. In addition, policies can include exemptions to avoid adverse effects on specific industries or economic activities. (6) International competitiveness: The sustainability of carbon tax policies under international competitive conditions also needs to be considered. If a country or region implements a carbon tax while other regions do not have similar policies, this may lead to enterprise transfer or unfair trade. Therefore, the treatment of exported and imported products is also an important design element. (7) Social acceptance: The design of carbon tax policies needs to consider public acceptance and social justice issues. Policies can adopt a gradual increase approach to balance economic and social interests and avoid unfair impacts on low-income groups.

In short, by designing reasonable tax rates, collection scopes, tax purposes, tax application methods, and tax elasticity, emission reduction targets can be more effectively achieved and sustainable development can be promoted.

4. Model Construction and Scenario Setting

4.1. Framework of CGE Model

According to the research purpose of this article and the structure of the general CGE model, the CGE model framework used in this article is shown in Figure 1.

Usually, the general CGE model includes economic entities such as residents, enterprises, government, and foreign countries. This article will also include these four types of entities, which is also a relatively comprehensive economic entity model. The market includes the commodity market and the factor market. In addition, the model in this article is a research model targeting the entire country of China. The CGE model constructed in this article is a model of two markets and four entities. The specific mathematical equations include modules such as production, enterprises, residents, trade, government, balance, and social welfare. Based on this, according to the research objectives of this article, two new modules have been included: the atmospheric pollutant and greenhouse gas accounting module and the environmental and economic policy module. Firstly, due to the research on the effectiveness of pollution reduction and carbon reduction policies in this article, a policy module needs to be embedded. Secondly, the research object of this article is the synergistic governance effect of air pollution and climate change; therefore, a module for pollutant and greenhouse gas accounting is required.

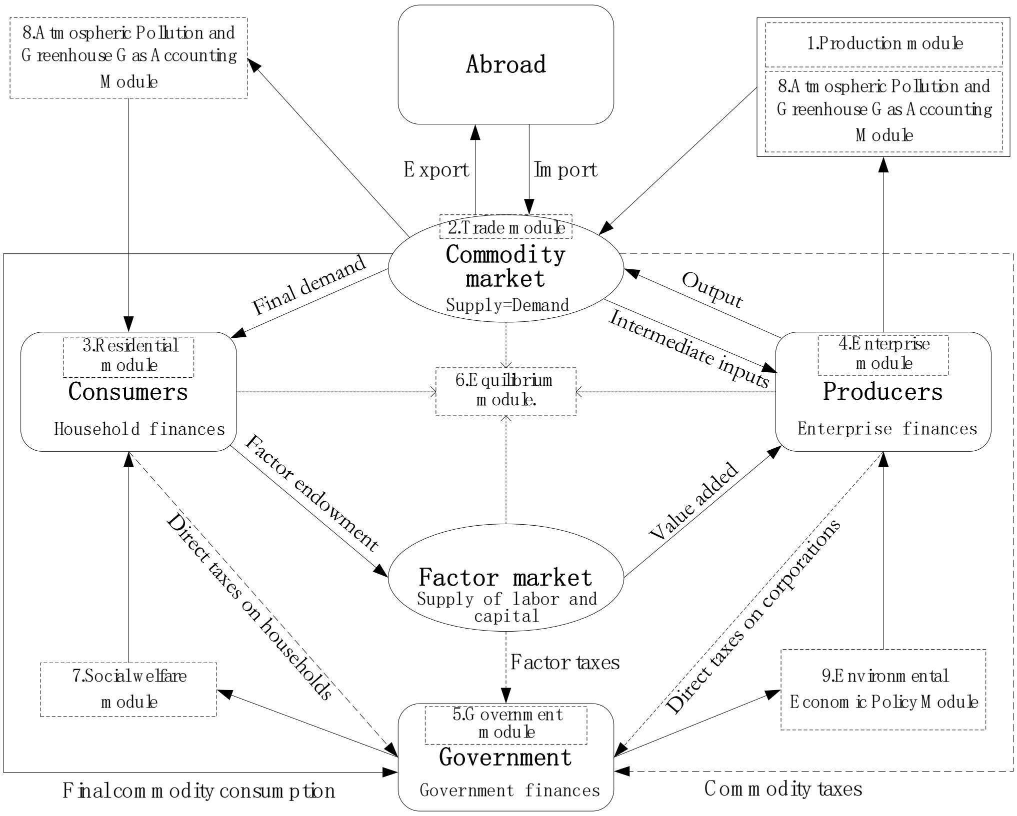

Figure 1. CGE Model Framework.

4.2. Department Division and Data Sources of CGE Model

The division of industry sectors in the CGE model varies depending on the research objectives. This article studies the effects of environmental and economic policies. As carbon market policies target the eight major industries with severe carbon emissions, this article determines the sectors of the CGE model based on the division of industries and the three major industries that need to be included in the carbon market in China.

Based on the industries covered by the carbon market and the division of the three major industries, the CGE model department division in this article is shown in Table 1.

Table 1. Division of CGE Models in this article.

Number	Industry	Category
1	Petrifaction	Industries covered by the national carbon market
2	Chemical industry	
3	Building materials	
4	Steel	
5	Colored	
6	Papermaking	
7	Electricity (thermal power)	
8	Aviation	
9	Agriculture	Primary industry
10	Other secondary industries	Secondary industry
11	Tertiary industry (excluding aviation)	Tertiary industry
12	Coal	Energy industry
13	Petroleum	
14	Natural gas	
15	New energy power generation	

The data sources are the 2020 China input–output table and the China Statistical Yearbook, and the 2020 China Social Accounting Matrix (SAM Table) has been prepared for this article. The division of departments in the SAM table is based on the standards in Table 1, and the data are merged based on the corresponding department data in the 2020 input–output table. Among them, the power sector is divided into the thermal power generation sector and the new energy generation sector, and the data-splitting ratio is based on the ratio of thermal power to the production of other electricity in 2020. Because there is no distinction between oil extraction and natural gas in the input–output table, it is necessary to split the natural gas sector from the oil sector, which is based on the ratio of oil to natural gas consumption in 2020. In addition, various parameters of the CGE model were calibrated based on the relevant research literature [12,22,39]. The carbon dioxide emission coefficient is calculated directly based on the actual amount of fossil energy consumed in China and the CO_2 emissions using the International Energy Statistics data from the International Energy Agency; the emission coefficient of sulfur dioxide is calculated using the physical consumption of energy and the total sulfur content.

4.3. Construction of CGE Model

This article constructs a CGE model based on references from Guo (2011) [39], Lou (2014) [22], He et al. (2002) [12], Zhang (2010) [40], and Lofgren et al. (2001) [41]. It mainly includes six modules: a production module, trade module, institutional module, social welfare module, atmospheric pollutant and greenhouse gas accounting module, and equilibrium and closure module.

(1) Production module

In the production module, the production function describes the capital, labor, energy, and intermediate inputs used by each department to obtain output. The production function consists of a 5-layer nested invariant substitution elasticity function (CES production function), as shown in Figure 2. The bottom layer is the synthesis of coal, oil, and natural gas, as well as the synthesis of thermal power and new energy generation; the second layer is the synthesis of non-electric energy and electric energy; the third layer is the synthesis of energy and capital; the fourth layer is the synthesis of capital energy and labor input; and the fifth layer is the synthesis of capital energy labor and intermediate inputs.

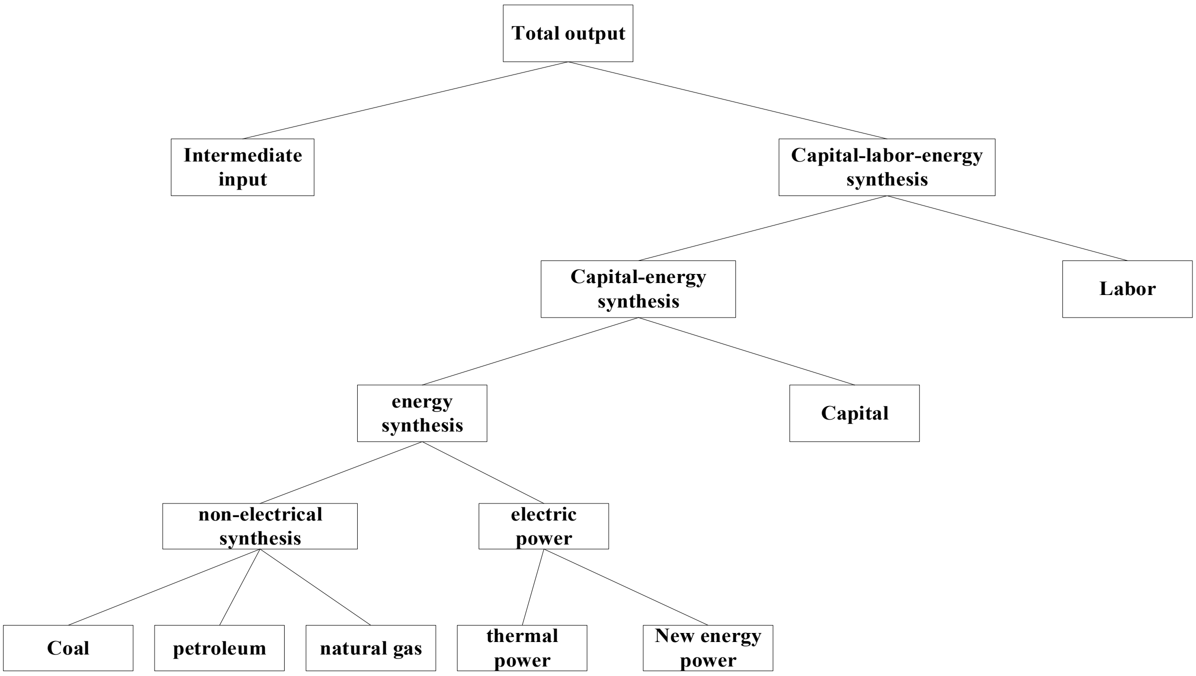

Figure 2. Structure of multi-layer nested production functions.

(2) Trade module

Some of the domestically produced goods are used for export and some are used for domestic consumption. In addition to domestically produced goods, there is also a portion of the total demand for goods in the domestic market that is imported to meet the demand (see Figure 3). Therefore, domestic manufacturers need to make decisions between the domestic and foreign markets in order to maximize producer profits. The optimal combination of goods for domestic sales or export depends on their prices and the conversion elasticity between them. The demand for domestic products adopts the Armington assumption and CES function. The distribution function of domestic products adopts the invariant transformation elasticity function (CET function).

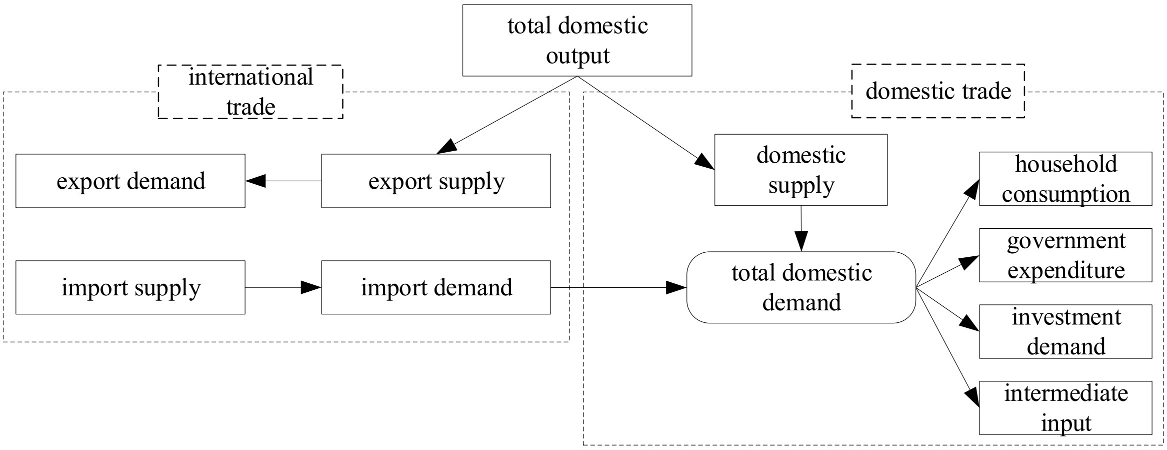

Figure 3. Trade module in CGE model.

(3) Institutional module

The institutions in the model mainly include residents, enterprises, and governments. The residents module includes functions for residents' income and expenditure, with residents' income mainly coming from labor income, capital income, and government transfer payments; resident expenditure mainly includes resident consumption, resident income tax, and resident savings. The enterprise module includes two parts: the income and expenditure of the enterprise. The income of the enterprise mainly comes from domestic and foreign capital investment income, and the enterprise expenditure consists of savings, investment, and transfer payments to residents. The government module describes the government's revenue and expenditure relationship. Government revenue generally consists of various taxes, while government expenditure includes government transfer payments, consumption, and savings.

(4) Social Welfare Module

The commonly used measure of social welfare changes in the CGE model is the Hichsian equivalent variation. This article uses the Hicks equivalence change to measure the impact of implementing carbon tax policies on residents' social welfare. The Hicks equivalent change is based on the commodity prices before the implementation of the policy, and measures the changes in residents' utility levels before and after the implementation of the policy. A positive change in the Hicks equivalence indicates that the welfare of residents has improved after the implementation of the policy. On the contrary, if the change is negative, it indicates that the implementation of the policy will harm the welfare of residents. The calculation formula is as follows:

$$\Delta CD = C(U_1, PQ) - C(U_2, PQ) = \sum_i PQ_i \cdot HD_i^1 - \sum_i PQ_i \cdot HD_i^2$$

The variable symbols and their meanings in the above formula are shown in Table 2.

Table 2. Variable symbols and their meanings in part (4).

Variable	Meaning
ΔCD	Changes in residents' welfare
$C(U_1, PQ)$	Utility level after policy changes
$C(U_2, PQ)$	Utility level before policy changes
PQ_i	The price of the *i*-th commodity before the policy change
HD_i^1	Consumption of the *i*-th commodity before policy changes
HD_i^2	Consumption of the *i*-th commodity after policy changes

(5) Atmospheric pollutants and greenhouse gas accounting module

The emissions of atmospheric pollutants and greenhouse gases are calculated separately for fossil energy use and sector output. The former refers to the emissions generated by fossil energy combustion, while the latter refers to the emissions generated by physical and chemical reactions in production processes. The accounting equation for atmospheric pollutants and greenhouse gas emissions is as follows (this article focuses on SO_2 and CO_2 as research objects):

SO_2 equation using fossil energy emissions:

$$ESO_2 = \varepsilon_i^s \cdot E_i$$

The equation for SO_2 emissions from departmental production processes:

$$GSO_2 = \sum_j \theta_j^s \cdot QX_j$$

Total SO_2 emissions:

$$TSO_2 = ESO_2 + QSO_2$$

CO_2 equation using fossil energy emissions:

$$ECO_2 = \varepsilon_i^c \cdot E_i$$

CO_2 equation for departmental production process emissions:

$$GCO_2 = \sum_j \theta_j^c \cdot QX_j$$

Total CO_2 emissions:

$$TCO_2 = ECO_2 + QCO_2$$

The variable symbols and their meanings in the above formula are shown in Table 3.

Table 3. Variable symbols and their meanings in part (5).

Variable	Meaning
ESO_2	Emissions of SO_2 from fossil fuel use
E_i, i = coal, oil, gas	Consumption of the *i*-th fossil fuel type
ε_i^s	The emission factor of SO_2 for the *i*-th type of fossil fuel
GSO_2	SO_2 emissions from the production processes of the sector
θ_j^s	The emission factor of SO_2 for the production of unit product in sector *j*
QX_j	The total output of sector *j*
TSO_2	Total SO_2 emissions
ECO_2	Emissions of CO_2 from fossil fuel use
ε_i^c	*i*-th type of fossil fuel CO_2 emission factor
GCO_2	CO_2 emissions from the production processes of the sector
θ_j^c	The emission factor of CO_2 for the production of a unit product in sector *j*
TCO_2	Total CO_2 emissions

(6) Equalization and closure module

The equilibrium and closure module describes the conditions that need to be satisfied for an economic system to achieve equilibrium. This module is based on the market clearing mechanism, considering factors such as the balance of payments, savings and investment, and market clearance. It is also the condition required for the CGE model to have a unique solution. The market clearing equilibria include the following: ① Labor market equilibrium: In this study, wages are assumed to be endogenous variables. After the policy shock, wage adjustments lead to the clearing of the labor market. ② Capital market equilibrium: Capital relative prices are assumed to be endogenous variables. After the economic policy shock, changes in capital prices lead to free capital movement, the full adjustment of enterprise capital stocks, and ultimately the efficient use of capital. ③ Product market equilibrium: The demand for each sector's products (residential demand, government demand, investment, inventory, intermediate demand) equals total supply. The macro closure of the model is reflected through three main macro identities: ① Savings and investment balance: In this study, the neoclassical closure rule is adopted, meaning that investment is determined by savings, and all savings in the economy will be transformed into investment. ② Government budget balance: Here, the difference between government revenue and total expenditure is defined as government savings, which is endogenously determined by the balance of government accounts. ③ Balance of payments: In this study, the exchange rate is assumed to be an endogenous variable, while foreign savings are exogenous variables. Policy shocks affect changes in exchange rates, which in turn affect imports and exports, and ultimately the entire economy.

4.4. Carbon Tax Policy Module and Link to CGE Model

Considering the use of carbon dioxide emissions as the basis for carbon tax calculation, the specific model is as follows:

Carbon tax amount for using fossil fuels in department *i*:

$$ECTAX_i = tc \cdot \sum_j ECO_{2ij}$$

Industrial process carbon tax amount for department *i*:

$$GCTAX_i = tc \cdot GCO_{2i}$$

Carbon tax amount for each fossil energy emission:

$$HECTAX_j = tc \cdot HECO_{2j}$$

Total carbon tax amount:

$$TCTAX = \sum_i GCTAX_i + \sum_j HECTAX_j$$

Once the carbon tax amount for fossil fuels is determined, the ad valorem tax rate for fossil fuels can be accurately calculated. Specifically, the ad valorem tax rate refers to the ratio of carbon tax to the total demand value of fossil energy. This indicator is the basis for the correlation of fossil energy emissions with the CGE models. The calculation formula is as follows:

$$t_{cj} = \frac{HECTAX_j}{PQ_j \cdot QQ_j}$$

As a result, the prices of various fossil fuels will become reflected in the energy costs in the production function, affecting the production costs of enterprises and thus affecting the entire economic system.

$$(1 + t_{cj})PQ_j$$

The amount of tax on industrial process emissions will directly affect the price of enterprise products, which is the foundation of the link between industrial process emissions and CGE models. The formula is as follows:

$$PX_i \cdot X_i = PP_i \cdot X_i + GCTAX_i$$

As a result, the price of the product has changed from PPi to PXi.

At the same time, the government's revenue function will also increase due to the collection of carbon taxes, and the total government revenue will be as follows:

$$YGT = \sum_i GINDTAX_i + \sum_i GTRIFM_i + GHTAX + GETAX + GWY + TCTAX$$

The variable symbols and their meanings in the above formula are shown in Table 4.

Table 4. Variable symbols and their meanings in Section 4.4.

Variable	Meaning
$TCTAX$	Total carbon tax amount
tc	Carbon tax rate, the amount of carbon tax levied per ton of CO_2 emissions
$ECTAX_i$	Carbon tax amount on the use of fossil fuels by department i
ECO_{2ij}	CO_2 emissions from sector i using j fossil fuels
$GCTAX_i$	Industrial process carbon tax amount for department i
GCO_{2i}	CO_2 emissions from industrial processes in sector i
$HECTAX_j$	Carbon tax amount for the j-th fossil energy source
$HECO_{2j}$	CO_2 emissions from the j-th fossil energy source
t_{cj}	Carbon tax rate for fossil energy j

4.5. Scenario Settings

Although China has not yet started implementing a carbon tax, in 2010, the country proposed a carbon tax implementation plan. This provides direction and guidance for China's carbon tax research and practice, and also demonstrates the determination of the Chinese government in addressing climate change and achieving sustainable development. With carbon emissions becoming a global focus, Chinese scholars' research on carbon taxes is also increasing. Many scholars have begun to explore the theoretical basis and policies of carbon taxes.

Design and practical experience have formed a hot topic in China's carbon tax research. Ma (2020) [42] studied the design of differentiated carbon tax policies and proposed three models: a fixed unified tax rate, a fixed differentiated tax rate, and a dynamic differentiated tax rate, with a tax rate range of 20–200 CNY/ton. Zhu et al. (2010) [43] studied the emission reduction effect and economic impact of carbon tax policies by setting three tax rates: 20 CNY/ton, 50 CNY/ton, and 100 CNY/ton. Lou (2014) [22] simulated carbon tax rates ranging from 40 CNY/ton to 70 CNY/ton under different targets. Guo et al. (2018) [43] studied the impact on the economy under a carbon tax scenario of 30 CNY/ton. Tang et al. (2020) [24] set up five carbon tax scenarios, namely CNY 200, CNY 220, CNY 260, CNY 280, and CNY 300 per ton, to simulate the impact on macroeconomic factors. Weng et al. (2021) [29] set four different levels of carbon taxes, namely CNY 120, CNY 100, CNY 80, and CNY 60 per ton. Liu et al. (2023) [44] studied the issue of China's energy economy transformation. After comparing the carbon tax rates of international countries, they set up three carbon tax scenarios: high, medium, and low, which are CNY 600, CNY 400, and CNY 200 per ton, respectively. Scholars [45] have also studied the impact of China's carbon tax scenario on international capital flows, setting carbon taxes at USD 10, USD 15, and USD 30 per ton. Wu et al. (2022) [46] set the carbon tax in China at USD 5–10 per ton, while Nong et al. (2021) [47] set the carbon tax at USD 10 per ton. Based on the above literature review regarding carbon tax, this article takes the eight major industries included in the carbon market as tax targets (see Table 1), and sets five carbon tax scenarios, including 30 CNY/ton, 50 CNY/ton, 70 CNY/ton, 100 CNY/ton, and 130 CNY/ton, for simulation research on synergistic effects.

4.6. Implementation and Verification of the Model on the Computer

The model presented in this paper comprises over 800 equations and constitutes a set of non-linear systems. Solving these equations to achieve equilibrium is a core computation in CGE modeling, which requires specialized software and programming. In this study, the GAMS 28.2.0 (General Algebraic Modeling System) software, which is capable of computing large-scale non-linear system equations and is a powerful tool for solving CGE models, was used for programming and solving.

To verify the effectiveness of the CGE model and GAMS program, the following five requirements must be satisfied: First, the basic assumptions of the model or program should correspond to reality and reflect the essential characteristics of the economy being studied. Second, comprehensive data collection and processing must be undertaken to ensure the reliability and representativeness of the data used. Third, appropriate model validation and sensitivity analysis should be conducted to further confirm the robustness and reliability of the results, including tests for price homogeneity, variable consistency, and whether Walras' variables equal zero. Fourth, different simulation experiments should be performed as per practical needs to evaluate the effects of various policies and for further optimization. Lastly, an empirical analysis should be performed to compare the results with actual situations to verify the real effectiveness and application prospects of the model or program.

The GAMS program for the CGE model in this paper meets the actual research requirements, with equations and variables consistent with one another, complying with the requirement of price homogeneity, and with Walras' variables equaling zero, indicating a certain level of stability in the model. Therefore, the GAMS program in this paper can pass the verification and can be used for the simulation studies discussed herein.

5. Analysis of Empirical Simulation Results

5.1. Analysis of Synergistic Emission Reduction Effects

After the implementation of carbon tax, under different carbon tax scenarios, CO_2 emissions gradually increase with the increase in carbon tax (see Table 5). The higher the carbon tax, the higher the carbon reduction rate. At the same time, because the tax targets energy use and industrial processes, sulfur dioxide emissions will also increase accordingly. However, overall, the reduction rate for sulfur dioxide is not as high as carbon dioxide, which is about 88.87% of the carbon dioxide reduction rate. Therefore, it can be concluded that carbon tax is also a policy path for coordinated pollution reduction and carbon reduction.

Table 5. Collaborative emission reduction of CO_2 and SO_2 under different carbon tax scenarios.

Carbon Tax	30 CNY/ton	50 CNY/ton	70 CNY/ton	100 CNY/ton	130 CNY/ton
CO_2 reduction (10,000 tons)	122,328.83	191,240.89	251,785.81	329,508.70	394,319.63
Emission reduction rate	−11.54%	−18.04%	−23.75%	−31.08%	−37.20%
SO_2 emission reduction (10,000 tons)	32.62	51.01	67.16	87.91	105.22
Emission reduction rate	−10.25%	−16.03%	−21.11%	−27.63%	−33.07%

Tables 6 and 7 show the synergistic emission reduction of carbon dioxide and sulfur dioxide in the sector. It can be seen from the data in the tables that all departments have experienced a decrease in carbon dioxide and sulfur dioxide emissions, except for the new energy generation department. Among them, departments that use coal energy more frequently, such as thermal power, coal, other secondary industries, the chemical industry, and building materials, have a greater reduction in emissions. Because coal has the highest emission coefficient, the sectors with coal as the main energy source have a large potential for emission reduction and a large reduction in emissions. Regarding the aviation industry, because the aviation fuel used is a processed product of petroleum, which is also a product of the petrochemical industry [48], the carbon emissions of the aviation industry are only calculated from the direct use of coal. The emissions of aviation fuel are calculated in relation to the petrochemical industry based on the input–output table.

Table 6. Reductions in carbon emissions by departments under different carbon tax scenarios (10,000 tons).

Carbon Tax	30 CNY/ton	50 CNY/ton	70 CNY/ton	100 CNY/ton	130 CNY/ton
Petrifaction	−861.31	−1437.33	−2014.01	−2879.63	−3745.69
Chemical industry	−6091.83	−9649.67	−12,863.96	−17,131.10	−20,834.13
Building materials	−4983.72	−7827.48	−10,342.49	−13,586.24	−16,298.04
Steel	−948.52	−1505.54	−2008.36	−2671.84	−3240.25
Colored	−1822.91	−2781.46	−3582.66	−4554.51	−5316.11
papermaking	−1567.36	−2454.23	−3233.26	−4229.67	−5054.44
Thermal power	−37,839.09	−59,816.64	−79,524.78	−105,370.00	−127,397.38
New Electricity	0.00	0.00	0.00	0.00	0.00
Aviation	−13.94	−19.50	−23.45	−28.47	−33.22
Agriculture	−533.71	−780.69	−969.05	−1175.14	−1319.16
Other	−42,852.67	−66,818.84	−87,766.71	−114,505.18	−136,682.44
Tertiary industry	−2356.37	−3440.85	−4266.48	−5169.63	−5801.94
Coal	−21,607.11	−33,333.55	−43,320.49	−55,633.84	−65,387.84
Petroleum	−73.38	−114.72	−151.11	−197.97	−237.32
nNtural gas	−21.25	−33.15	−43.56	−56.91	−68.03

Table 7. Reductions in sulfur emissions by departments under different carbon tax scenarios (10,000 tons).

Carbon Tax	30 CNY/ton	50 CNY/ton	70 CNY/ton	100 CNY/ton	130 CNY/ton
Petrifaction	−0.1458	−0.2478	−0.3533	−0.5171	−0.6873
Chemical industry	−1.6299	−2.5832	−3.4455	−4.5918	−5.5883
Building materials	−1.3236	−2.0789	−2.7470	−3.6088	−4.3294
Steel	−0.2517	−0.3995	−0.5330	−0.7091	−0.8599
Colored	−0.4850	−0.7401	−0.9534	−1.2121	−1.4150
papermaking	−0.4160	−0.6514	−0.8582	−1.1227	−1.3417
Thermal power	−10.0500	−15.8883	−21.1246	−27.9926	−33.8473
New Electricity	0.0000	0.0000	0.0000	0.0000	0.0000
Aviation	−0.0037	−0.0052	−0.0062	−0.0076	−0.0088
Agriculture	−0.1416	−0.2071	−0.2571	−0.3118	−0.3500
Other	−11.4649	−17.8832	−23.4975	−30.6705	−36.6266
Tertiary industry	−0.6258	−0.9139	−1.1332	−1.3731	−1.5410
Coal	−5.7334	−8.8450	−11.4951	−14.7624	−17.3507
Petroleum	−0.0207	−0.0323	−0.0426	−0.0559	−0.0671
Natural gas	−0.0060	−0.0094	−0.0123	−0.0161	−0.0193

5.2. Energy Consumption Analysis

Regarding the carbon emissions generated by the combustion of fossil fuels, a carbon tax policy will be implemented; as the emission coefficients of each fossil energy are different, different tax rates will be adopted. Table 8 shows the tax rates for various fossil fuels under the scenarios of carbon taxes of 30 CNY/ton, 50 CNY/ton, 70 CNY/ton, 100 CNY/ton, and 130 CNY/ton, respectively.

Table 8. Fossil energy carbon tax rates under various carbon tax scenarios.

Carbon Tax	30 CNY/ton	50 CNY/ton	70 CNY/ton	100 CNY/ton	130 CNY/ton
Coal	8.88%	14.80%	20.72%	29.60%	38.48%
Petroleum	2.67%	4.44%	6.22%	8.89%	11.56%
Natural gas	3.34%	5.56%	7.79%	11.13%	14.47%

It can be seen from Table 8 that with the increase in carbon tax, the tax rate of fossil energy gradually increases, of which the tax rate of coal is the highest. When the carbon tax is 130 CNY/ton, the ad valorem tax rate of coal will be close to 40%, while that of oil and natural gas is only 11.56% and 14.47%. The low ad valorem tax rate of oil and natural gas is mainly a result of the carbon emission coefficient of the three fossil energy sources being significantly lower than that of coal, and because coal accounts for a large proportion in the energy consumption structure; it is the main fossil energy used.

The carbon dioxide emitted by industrial processes is subject to a carbon tax on the industrial output. This article evaluates four industries with high industrial process emissions, while the industrial process emissions of other industries with low or no emissions are not included. Different industries have different production volumes; therefore, their tax rates also vary. Table 9 shows the carbon tax rates levied by various industries on carbon dioxide emissions for industrial processes under different carbon tax scenarios.

Table 9. Industrial process carbon tax rates under different carbon tax scenarios.

Carbon Tax	30 CNY/ton	50 CNY/ton	70 CNY/ton	100 CNY/ton	130 CNY/ton
Chemical industry	0.06%	0.11%	0.15%	0.21%	0.28%
Building materials	0.68%	1.14%	1.59%	2.28%	2.96%
Steel	4.30%	7.16%	10.03%	14.32%	18.62%
Tertiary industry	0.01%	0.02%	0.03%	0.04%	0.05%

From Table 9, it can be seen that the steel industry has the highest tax rate, followed by building materials, thermal power, and the tertiary industry. In the process of steel smelting, the ironmaking process involves the reduction of iron ore, coke, and solvents in the blast furnace to produce molten iron. During this process, the CO generated by coke reduces iron and generates CO_2. In addition, during the steelmaking process, the carbon in the molten iron is oxidized, generating CO_2. These two steps are the process steps that generate the most CO_2. The building materials industry mainly generates CO_2 through the decomposition of carbonate raw materials in industrial production processes, with the CO_2 emissions from cement and lime industrial processes ranking among the top two in the building materials industry. The desulfurization agent used in the thermal power industry is carbonate, which generates CO_2. The tertiary industry also has a small amount of non-energy combustion carbon emissions. Among them, the industrial process carbon tax rate of the steel industry is significantly higher than that of other industries, reaching 18.62%; this is followed by the building materials industry, reaching 2.96%. The industrial process carbon emissions of these two industries cannot be underestimated.

According to Table 10, there have been significant changes in the consumption of fossil fuels under different carbon tax scenarios. Specifically, with the gradual increase in carbon tax, the consumption of coal, oil and natural gas shows a gradual downward trend, of which the decline in coal is the most significant. This is because, in China's fossil energy consumption, carbon dioxide emissions mainly come from coal, so in the process of taxation, coal has suffered the greatest impact, and its tax rate and price have also risen the most. This will undoubtedly encourage enterprises to reduce their demand for coal by reducing production costs, resulting in the largest decrease in its consumption. It is worth mentioning that emissions generated in the electricity industry, as a substitute for energy consumption, are showing an increasing trend. This indicates that in the process of responding to carbon tax collection, enterprises have gradually realized the importance of energy conservation and emission reduction, and are gradually replacing the consumption of fossil energy. Although this has brought new challenges to the power industry, it has also brought more development opportunities for enterprises.

Table 10. Impact of energy consumption.

Carbon Tax	30 CNY/ton	50 CNY/ton	70 CNY/ton	100 CNY/ton	130 CNY/ton
Coal	−15.5406%	−24.2399%	−31.8439%	−41.5425%	−49.5640%
Petroleum	−2.3571%	−3.8311%	−5.2284%	−7.1863%	−8.9892%
Natural gas	−3.1495%	−5.1038%	−6.9472%	−9.5171%	−11.8718%
Thermal power	3.7499%	6.1335%	8.4083%	11.6032%	14.4253%
New electricity	3.7499%	6.1335%	8.4083%	11.6032%	14.4253%

5.3. Analysis of Industry Output and Price Level

Tables 11 and 12 show the results of changes in the output and prices across various sectors due to the imposition of carbon taxes. According to the data, prices in various industries have risen, mainly due to the increase in production costs caused by the implementation of carbon taxes. Specifically, industries that consume more fossil fuels, such as steel, building materials, chemicals, and coal, have seen significant price increases; industries that consume fewer fossil fuels, such as aviation, agriculture, and the tertiary industry, have seen relatively small price increases. Among the 15 industries, sectors such as power generation, aviation, and the tertiary industry have seen an increase in output, while other sectors have shown varying degrees of decline. In particular, in sectors such as coal, natural gas, petroleum, non-ferrous metals, chemicals, steel, and building materials, the proportion of decline is relatively large.

The high demand for energy in sectors such as iron, coal, natural gas, and oil has led to a high proportion of energy input during production. The imposition of a carbon tax has significantly increased the production costs of these sectors, resulting in a decrease in supply. On the other hand, the decrease in demand is partly attributed to the high increase in product prices in these sectors, leading to a decrease in demand. The simultaneous decrease in supply and demand leads to a decrease in production. The cost increase in industries such as aviation, the tertiary industry, and new energy power generation is relatively small, so the decline in supply is relatively low. Compared to industries with high energy costs, the prices of these three industries are lower, so product demand will increase. Therefore, the combined effect of supply and demand factors will lead to an increase in output in all departments. In addition, thermal power generation and new energy generation are substitutes for other energy sources, and their demand will also increase.

Overall, with the gradual increase of carbon tax, product prices are also increasing; meanwhile, the output of sectors such as steel, petrochemicals, building materials, chemicals, coal, natural gas, and oil is continuously decreasing, and the output of sectors such as aviation, power generation, and tertiary industry is increasing.

Table 11. Impact of departmental outputs.

Carbon Tax	30 CNY/ton	50 CNY/ton	70 CNY/ton	100 CNY/ton	130 CNY/ton
Petrifaction	−0.0774%	−0.1319%	−0.1879%	−0.2735%	−0.3601%
Chemical industry	−0.2144%	−0.3447%	−0.4665%	−0.6359%	−0.7926%
Building materials	−0.2743%	−0.4373%	−0.5875%	−0.7929%	−0.9794%
Steel	−0.2894%	−0.4631%	−0.6242%	−0.8462%	−1.0493%
Colored	−0.2325%	−0.3711%	−0.4989%	−0.6745%	−0.8348%
papermaking	−0.1016%	−0.1712%	−0.2413%	−0.3467%	−0.4513%
Thermal power	0.7470%	1.2333%	1.7032%	2.3692%	2.9816%
New electricity	0.7470%	1.2333%	1.7032%	2.3692%	2.9816%
Aviation	0.0053%	0.0081%	0.0112%	0.0154%	0.0191%
Agriculture	−0.0014%	−0.0045%	−0.0074%	−0.0113%	−0.0158%
Other	−0.2329%	−0.3716%	−0.4997%	−0.6754%	−0.8359%
Tertiary industry	0.0865%	0.1166%	0.1301%	0.1570%	0.1836%
Coal	−15.5159%	−24.2020%	−31.7952%	−41.4807%	−49.4924%
Petroleum	−2.3672%	−3.8486%	−5.2538%	−7.2247%	−9.0417%
Natural gas	−3.1685%	−5.1386%	−7.0004%	−9.6029%	−11.9952%

Table 12. Impact of departmental product prices.

Carbon Tax	30 CNY/ton	50 CNY/ton	70 CNY/ton	100 CNY/ton	130 CNY/ton
Petrifaction	0.0067%	0.0110%	0.0151%	0.0210%	0.0265%
Chemical industry	0.0392%	0.0641%	0.0881%	0.1223%	0.1546%
Building materials	0.0601%	0.0984%	0.1351%	0.1877%	0.2372%
Steel	0.0854%	0.1397%	0.1920%	0.2666%	0.3370%
Colored	0.0611%	0.1000%	0.1374%	0.1907%	0.2410%
papermaking	0.0652%	0.1067%	0.1466%	0.2036%	0.2573%
Thermal power	0.0278%	0.0454%	0.0624%	0.0867%	0.1095%
New electricity	0.0399%	0.0654%	0.0898%	0.1247%	0.1576%
Aviation	0.0010%	0.0034%	0.0051%	0.0070%	0.0095%
Agriculture	0.0012%	0.0044%	0.0076%	0.0110%	0.0158%
Other	0.1835%	0.3004%	0.4128%	0.5735%	0.7251%
Tertiary industry	0.0026%	0.0048%	0.0062%	0.0083%	0.0101%
Coal	0.1198%	0.1961%	0.2695%	0.3743%	0.4731%
Petroleum	0.0682%	0.1116%	0.1533%	0.2129%	0.2691%
Natural gas	0.0682%	0.1116%	0.1533%	0.2129%	0.2691%

5.4. Macroeconomic Impact Analysis

Table 13 reveals the response of macroeconomic variables to carbon taxes. For residents, the decrease in capital income has led to a decrease in total income, and coupled with the impact of rising product prices, residents' consumption demand and savings have been suppressed. With the continuous increase in carbon tax, the decline in residents' demand gradually intensifies, leading to a decrease in social welfare levels. For enterprises, capital income is the most important source of income, so the imposition of carbon tax leads to a decrease in capital prices, which in turn affects the income and savings of enterprises. The main source of government revenue comes from taxation, and although the government's indirect taxes may decrease due to a decrease in output, the corresponding corporate income tax will also increase. In addition, the introduction of a carbon tax has increased government revenue. Despite the increase in product prices, government consumption has still increased, and government savings have also slightly increased.

Table 13. Macroeconomic impacts under different carbon tax scenarios.

Carbon Tax	30 CNY/ton	50 CNY/ton	70 CNY/ton	100 CNY/ton	130 CNY/ton
Nominal GDP	−0.3457%	−0.5601%	−0.7627%	−1.0465%	−1.3088%
Real GDP	−0.0798%	−0.1505%	−0.2307%	−0.3624%	−0.5017%
Social welfare	−462.2317	−770.4877	−1077.3809	−1533.8098	−1984.8390
Resident income	−0.0947%	−0.1588%	−0.2232%	−0.3200%	−0.4164%
Resident demand	−0.1185%	−0.1975%	−0.2761%	−0.3931%	−0.5087%
Resident savings	−0.0947%	−0.1588%	−0.2232%	−0.3200%	−0.4164%
Total revenue of the enterprise	−0.4474%	−0.7248%	−0.9869%	−1.3543%	−1.6941%
Enterprise savings	−0.4474%	−0.7248%	−0.9869%	−1.3543%	−1.6941%
Government revenue	1.2170%	1.8520%	2.3778%	3.0073%	3.4934%
Government savings	1.2170%	1.8520%	2.3778%	3.0073%	3.4934%
Government consumption	1.2048%	1.8314%	2.3488%	2.9656%	3.4389%
Total investment	−0.2683%	−0.4228%	−0.5622%	−0.7494%	−0.9171%
Carbon strength	−11.4688%	−17.9164%	−23.5749%	−30.8322%	−36.8799%

The nominal GDP is equal to the sum of the total capital income, the total labor income, and the indirect tax income. The decrease in total capital income has led to a continuous decline in nominal GDP. Although the labor income remains unchanged, the overall decline in output is due to the overall increase in output prices, and the indirect tax income does not account for a large proportion. This continues the downward trend in nominal GDP.

Real GDP equals the sum of consumption, investment, and net exports. Resident consumption, government consumption, and investment (i.e., savings) are all affected by carbon tax policies. In terms of consumption, residents' consumption has decreased. Although government consumption has increased, overall consumption has still decreased. In terms of savings, as the main component of savings, the savings of enterprises have significantly decreased, and overall savings have also decreased, leading to a decrease in investment. The net export price is affected by the increase in domestic product prices and the unchanged foreign prices, which reduces the net export price. Therefore, the actual GDP is not only affected by consumption and investment, but also by net exports. Overall, these interactions have led to a decrease in real GDP.

Although the downward trend of actual GDP is obvious, the decrease in actual GDP is not significant compared to the total reduction in carbon dioxide emissions. Therefore, the carbon tax policy has been proven to be an effective emission reduction policy that can help reduce the overall intensity of carbon dioxide emissions.

Overall, with the continuous increase in carbon tax, the decline in real GDP, nominal GDP, social welfare, total corporate income, and carbon intensity gradually increases, but the increase in total government income gradually increases.

5.5. Robustness Testing of the Model

The elasticity of substitution between energy elements in the production function is directly related to the difficulty of substituting between energy sources, which leads to the policies implemented in order to reduce sulfur and carbon emissions having an impact on energy consumption, emission reductions, and economic variables. Therefore, the robustness of the model used in this article was tested to analyze its impact on the total emissions, carbon intensity, GDP, and energy consumption by increasing the substitution elasticity between electricity and energy by 30% and decreasing it by 30% under the scenario of a carbon tax of 130 CNY/ton (Table 14).

Table 14. Analysis of the robustness test results of the carbon tax policy model.

Variable	30% Increase in Substitution Elasticity of Electric Energy	30% Reduction in Substitution Elasticity of Electric Energy
Total CO_2 emissions	$5.75276 \times 10^{-12}\%$	$6.32979 \times 10^{-12}\%$
Total SO_2 emissions	$6.09681 \times 10^{-12}\%$	$5.74215 \times 10^{-12}\%$
Carbon strength	$5.23121 \times 10^{-12}\%$	$1.20905 \times 10^{-11}\%$
GDP	$-5.09901 \times 10^{-13}\%$	$3.70837 \times 10^{-13}\%$
Total energy consumption	$-6.48766 \times 10^{-12}\%$	$-1.92581 \times 10^{-12}\%$

From Table 14, it can be seen that when the substitution elasticity between electric energy sources changes, there is little difference in the changes in the total CO_2 and SO_2 emissions, carbon intensity, and GDP, indicating that the model has a certain degree of stability.

6. A Comparative Discussion on the Collaborative Control of Pollution Reduction and Carbon Reduction in Other Countries around the World

In the conclusion of this article, the G20 countries were selected as research subjects to explore the path patterns and historical experiences associated with the achievement of the collaborative prevention and control of air pollutants and greenhouse gases. The G20 comprises twenty countries/regions including China, France, Russia, the United Kingdom, the United States, and the European Union, with their GDP accounting for approximately 85% of the world's total, their populations making up about two-thirds of the global population, and their carbon emissions contributing to 80% of the world's total; these countries therefore play a significant leading role in the global governance of climate change. This study selected 19 countries from the G20 (China, Argentina, Australia, Brazil, Canada, France, Germany, India, Indonesia, Italy, Japan, South Korea, Mexico, Russia, Saudi Arabia, South Africa, Turkey, the United Kingdom, and the United States) as research subjects. Among them, there are countries like the United Kingdom and the United States, which at some point in history had similarities with China's current period, as well as countries like South Africa and Russia, which are in situations similar to the current state of China, offering certain representativeness and research value. The SO_2 and CO_2 data used in this study come from the International Energy Agency (IEA) and gridded emission inventory data released by Peking University (PKU series) (http://inventory.pku.edu.cn/home.html, accessed on 8 February 2022).

This study designed a coordinate system to assess the collaborative prevention and control effects, using different coordinates to express a country's emission reduction performance for various pollutants over a certain period. The x-axis represents the CO_2 reduction performance, and the y-axis represents the SO_2 reduction performance, with points in the coordinate system representing the collaborative emission reduction status of a country in a given year. Specifically, (1) points in the first quadrant indicate that the country has reduced emissions of both pollutants during this period, achieving collaborative reduction. (2) Points in the second quadrant indicate that the country has reduced SO_2 emissions but increased CO_2 emissions. (3) Points in the third quadrant indicate that the country has increased emissions of both pollutants during this period. (4) Points in the fourth quadrant indicate that the country has reduced CO_2 emissions but increased SO_2 emissions.

As shown in Figure 4, the United Kingdom, the United States, Germany, France, and Italy, which are currently in the first quadrant, are typical countries that have achieved collaborative prevention and control. Countries like China, Russia, Saudi Arabia, South Africa, Turkey, Mexico, Indonesia, South Korea, Japan, Australia, and Canada, which are in the second quadrant, have managed to reduce sulfur but have increasing carbon emissions. Countries like India, Brazil, and Argentina are in the third quadrant, where both carbon and sulfur emissions have been continuously increasing, indicating that, not only have they not achieved collaborative reduction, but their air pollutants and greenhouse gases are in a phase of simultaneous increase. Further analysis shows that countries in the same quadrant tend to have similar economic development stages, while those in different quadrants exhibit significant differences, such as in economic growth, energy structure, and industrial structure.

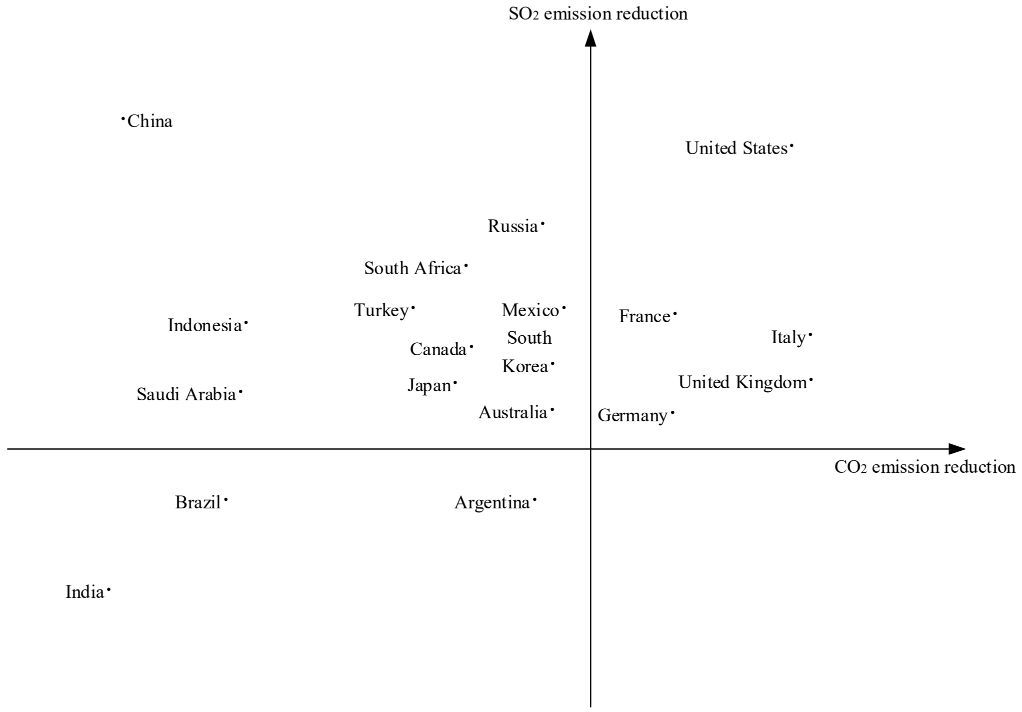

Figure 4. The current state of collaborative emission reduction efforts among 19 countries.

There are three representative pathways for collaborative prevention and control: (1) Countries like the United Kingdom are typical of those that have achieved the collaborative control of both carbon and sulfur reductions. These countries are usually long-established developed nations. (2) Countries like China represent those that have increasing carbon emissions but reducing sulfur emissions. These nations tend to be later-stage industrial developers with rapid economic growth phases that arrived later, prioritizing climate change issues but facing greater contradictions between developing their economy and reducing carbon emissions than the first category. (3) Countries like India represent those that see a continued increase in both carbon and sulfur emissions. These countries have relatively slow economic growth or have entered a bottleneck period, with poor domestic air pollution management and low international participation in climate change governance.

The research on the effectiveness of carbon taxes in reducing pollution and carbon emissions in this article can be extended to countries like China, which represents the second category.

7. Conclusion and Policy Implications

7.1. Conclusions

This article constructs a CGE model and its data foundation for studying synergistic effects. The CGE model constructed was used to simulate the synergistic emission reduction effect of carbon tax policies, and the following conclusions were drawn:

(1) After the implementation of a carbon tax policy, when the carbon tax increased from 30 CNY/ton to 130 CNY/ton, the CO_2 reduction increased from 1.223 billion tons to 3.943 billion tons. At the same time, the reduction in SO_2 increased from 326,200 tons to 1,052,200 tons. However, overall, the reduction rate of SO_2 was about 88.87% of the CO_2 reduction rate. Therefore, the carbon tax is also an effective policy path for synergistic pollution reduction and carbon mitigation.

(2) When a carbon tax policy is implemented, industries that consume more fossil energy, such as steel, building materials, the chemical industry, and coal, face larger price increases. Under the scenario of a carbon tax of CNY 130 per ton, their price increases are 0.3370%, 0.2372%, 0.1546%, and 0.4731%, respectively. For industries that consume less fossil energy, such as aviation, agriculture, and the tertiary industry, the price increases are smaller, at 0.0095%, 0.0158%, and 0.0101%, respectively. Among the 15 industries, sectors such as electricity, aviation, and the tertiary industry have increased their output, while the rest have shown decreases to varying degrees. Notably, the coal (−49.4924%), natural gas (−11.9952%), petroleum (−9.0417%), non-ferrous metals (−0.8348%), chemical industry (−0.7926%), steel (−1.0493%), and building material (−0.9794%) sectors have seen significant decreases. In terms of energy consumption, with the increase in carbon tax, the consumption of coal, oil, and natural gas all show a downward trend, with coal experiencing the largest decrease at −49.5640%.

7.2. Policy Implications

Based on the above conclusions, this article proposes the following policy recommendations:

(1) When implementing carbon tax policies, subsidies or other measures should be considered for industries that consume more fossil fuels in order to mitigate the impact of price increases on these industries and encourage them to reduce carbon emissions.

(2) The development of sectors such as power generation, aviation, and the tertiary industry should be supported to promote increased output, while industries with lower energy consumption, such as aviation, agriculture, and the tertiary industry, should be encouraged.

(3) Efforts to reduce emissions in sectors such as coal, natural gas, petroleum, non-ferrous metals, chemicals, steel, and building materials should be increased, and the transformation of these high-carbon-emission industries towards clean production and low-carbon technology should be promoted.

(4) In order to achieve better emission reduction results, the carbon tax rate should not be too low; otherwise, it will be difficult to continuously reduce the consumption of

coal, oil, and natural gas, and promote the application and development of renewable and clean energy.

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