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Research Article

Research on the Impact of Carbon Tax on CO_2 Emissions of China's Power Industry

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Based on the TIMES model, a system for CO_2 emission reduction in China's power industry is built in this paper. Four scenarios including different carbon tax levels are set up, simulating the CO_2 emissions of China's power industry in 2020–2050 by using scenario analysis method. The power consumption demand, primary energy consumption structure, CO_2 emission characteristics, emission reduction potential, and cost of different carbon tax levels are quantitatively studied. In combination with the impact on China's macroeconomy, the carbon tax level corresponding to the best CO_2 emission reduction effect of China's power industry is obtained, aiming to provide key data and a theoretical basis for China's low-carbon development as well as the optimization and adjustment of global power production system. The results show that with the development of economy and society in the future, China's power consumption demand will increase year by year, while the primary energy consumption of the power industry will maintain a rapid growth. The power industry still relies heavily on fossil energy, which will cause great pressure on China's economic development and ecological environment. Carbon tax will have an important impact on the primary energy supply structure of China's power industry, and renewable energy can be developed in different degrees. CO_2 emissions will be significantly reduced, reaching the peak value during 2030–2040 in China's power industry. The medium carbon tax level (TAX-2) set in this paper can meet the requirements of both CO_2 emission reduction effect and cost in the power industry, with the most elastic impact on the national economy and the smallest GDP loss, which can be used as an effective environmental economic policy tool.

1. Introduction

The issue of climate change is receiving widespread attention worldwide, making all sectors of society realize the importance of developing low-carbon economy and achieving sustainable development of society. The peak of greenhouse gas emissions is not only the critical point in the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) but also the focus of international climate negotiations in recent years. According to statistics, 40% of global CO_2 emissions come from power industry, 23% from transportation department, and 22% from cement plants, oil refineries, steel mills, etc. [1]. As a secondary energy, electric power plays an important role in economic development and industrial production, with a huge demand. With the development of economy, in order to ensure sufficient power supply, a large amount of primary energy needs to be consumed [2]. In China, fossil energy accounts for 89% of the total primary energy demand in 2015 [3]. The relationship between resource reserve and consumption in China is seriously imbalanced, and how to realize the coordinated development of environment and economy has become an urgent issue to be solved for the country. According to statistics from China's National Development and Reform Commission, in July 2017, 79.8% of China's total power generation came from coal-fired power plants [4]. This coal-based energy consumption and production structure lead to excessive dependence on coal in China's power production process and has a huge impact on the ecological environment. Therefore, it is very important to adjust the energy structure of China's power industry, whether from the perspective of solving the problem of increasing energy shortages or controlling CO_2 emissions. Reducing greenhouse gas emissions will become an urgent task for China's power industry and an inevitable direction for the energy structure adjustment of the global power production system [5].

Carbon tax is a kind of tax levied on fossil energy based on its carbon content or CO_2 emissions, so as to reduce CO_2 emissions and control the excessive use of fossil fuels [6]. In recent years, carbon tax has become an important mean of CO_2 prevention and control. Through the government's "invisible hand" to correct the externality of market economy, CO_2 emissions can be effectively reduced. In the process of levying carbon tax, on the one hand, the increase of cost will urge enterprises to actively eliminate backward production capacity and use renewable clean energy; on the other hand, the carbon tax will stimulate enterprises to invest a large amount of capital in research and development of emission reduction technologies. Under the mixed effect of multiple factors, the industrial structure will be adjusted and upgraded, with the domestic economic development mode changed from a traditional extensive model to a low-carbon economy [7]. This kind of "inverse effect" on microeconomic individuals can promote the transformation of the resource consumption structure while pushing the macroeconomy to a path of sustainable development, which ultimately leads to a "win-win" situation of economic development and environmental protection. As the second largest economic body in the world, China is not only the largest developing country, but also one of the countries with the largest CO_2 emissions. In order to alleviate the issue of greenhouse gas emissions, the Chinese government has put forward the 2030 CO_2 emission reduction independent action goal. For this task of energy conservation and emission reduction that China is going to accomplish, the power industry will be an important breakthrough point [8]. Therefore, it is urgent to study the low-carbon green development path of China's power industry in the future under the existing CO_2 emission constraints.

At present, the relevant research focuses on three aspects: CO_2 emission influencing factors, carbon tax impact, and analysis models.

Some scholars pay attention to the influencing factors of CO_2 emissions. Shipkovs et al. found that adjusting the energy consumption structure can effectively reduce greenhouse gas emissions [9]. Chen et al. found that the large-scale use of renewable energy can guarantee effective greenhouse gas control by studying China's future control strategies for major greenhouse gas emissions [10]. Using the ARDL model, Zhao et al. studied the effects of three factors, namely, industrial added value, average utilization hours of thermal power equipment, and standard coal consumption rate, on CO_2 emissions of power industry [11]. Zhang et al. found that the economic activity effect is the main reason for the increase of CO_2 emissions, while the production efficiency of electric power plays a key role in controlling CO_2 emissions [12]. However, these studies are mainly from the macrolevel, and there are obvious deficiencies in the energy system, especially in the power system.

Carbon tax policy is widely advocated and adopted as the most effective mean of emission reduction among the climate protection policies, which has been applied in different forms in many countries. Scholars have conducted a lot of research on carbon tax and its impact. Nordhaus used the DICE (Dynamic Integrated Climate-Economy) model to study the impact of different carbon tax levels on the ecological environment [13]. Peace studied that a reasonable carbon tax level can partially eliminate the negative impact on the economy. It can not only promote enterprises to adjust their production and operation activities to reduce emissions, but also use the revenue for other ecological construction [14]. Floros studied the impact of carbon tax on the CO_2 emissions of energy manufacturing industry in Greece and found that reasonable carbon tax policies can further reduce the accumulated CO_2 stock in the atmosphere and then mitigate the phenomenon of climate degradation [15]. Although carbon tax has not been included in the environmental tax currently levied in China, in view of its positive and systematic effect on the ecological environment, the research on carbon tax has attracted widespread attention from Chinese scholars. He et al. studied the data of 55 countries in the past 20 years and found that the implementation of carbon tax can help reduce CO_2 emissions and significantly improve the local environmental quality [16]. Zhu et al. analyzed the necessity and feasibility of carbon tax in China, put forward the basic objectives and principles of carbon tax, preliminarily designed the basic content, and specifically proposed the implementation framework of carbon tax system [17]. However, there are few reports on the carbon tax research of China's power industry; the low-carbon path for China's power industry to promote emission reduction through carbon tax has not been clear.

In the current research based on 3E (energy-economy-environment) systems, the widely used models mainly include the MARKAL (Market Allocation of Technologies Model) [18], the LEAP (Long-Range Energy Alternatives Planning) model [19], the CGE (Computable General Equilibrium) model [20], the Input-Output model [21], the System Dynamics model [22], and the Logistic Regression model [23]. These analytical models used in low-carbon research can be divided into "top-down" energy economic models and "bottom-up" energy technology models according to the research methods and model frameworks [24]. Of these, the energy economic model mainly simulates the real economic system, and the model subject is the various factor providers and consumers who seek to maximize utility. It is widely used in the study of energy environmental economic policies. The energy technology model is a large dynamic energy optimization model developed by international research institutions that is widely used in research on energy system optimization and emission reduction at the national, regional, and industry levels [25]. Compared with the energy technology model, the energy economy model focuses on the connection between the energy sector and other sectors but does not analyze the technical factors of the internal energy system. The energy technology model is more suitable for low-carbon research in the power industry because it offers comprehensive analysis, calculation, and optimization from the perspective of energy supply, conversion, and demand. Researchers mainly use MARKAL and TIMES (The Integrated MARKAL-EFOM System) for modeling research. Van et al. established a MARKAL model for the Dutch power system and set up a large number of scenarios, repeatedly verifying to obtain the optimal power planning, including the selection of environmental policies, the establishment plan of power plants, and the amount of capital invested in carbon capture technology [26]. Jegarl et al. established a MARKAL model for the Korean power system, simulated different policy options and technology combinations, and evaluated these policies based on the obtained results [27]. Jia and Liu used the TIMES model to analyze the impact of energy conservation and emission reduction policies and measures on energy supply and demand as well as air pollutant emissions in Beijing for 2010–2020 [28]. Daly et al. used the TIMES model to study the impact of Iranian residents' travel cost on the CO_2 emissions of the transport department [29]. The above studies have shown that the energy technology model has better applicability in the energy-environment field, and it is more suitable for low-carbon research in the power industry.

In summary, this paper constructs a theoretical analysis model of CO_2 emission characteristics of China's power industry and studies the corresponding temporal evolution characteristics by integrating technology optimization, energy structure adjustment, CO_2 emissions, and carbon tax impact into the traditional economic growth analysis framework.

2. Materials and Methods

2.1. TIMES Model. As a "bottom-up" energy technology model, the TIMES model is a new generation of a comprehensive climate change evaluation model developed by the ETSAP (Energy Technology Systems Analysis Program) model based on the MARKAL model, and it integrates the advantages of EFOM (Energy Flow Optimization Model). The TIMES model is generally used to simulate the entire energy system, and it is also used to study individual specific industries, such as transportation industry or steel industry. It has a wide research scope, such as the impact of technological progress on energy demand, production and conversion, the mutual substitution of various energy sources, energy investment and system cost, and the impact of reducing greenhouse gas emissions on energy system and economy. The model can describe the various links of exploitation, processing, conversion, distribution, and terminal energy consumption in the energy system in detail. For each link, existing technologies and various advanced technologies and related alternatives that may appear in the future can be considered. It is a dynamic linear programming model which assumes that the energy system is in a state of complete competition; it seeks to maximize the total net surplus and simulates the market equilibrium. In the model, the maximum total net surplus of the energy system is converted into the minimum total net cost of the energy system. On this basis, the model not only meets the demand of terminal energy services but also selects the technology combination with the lowest cost. In recent years, the model has been used in the economic analysis of climate and energy policies in approximately 70 countries. Numerous studies have shown that the TIMES model has good applicability in the energy-environment field [30, 31].

Based on the powerful technical features and the characteristics that can be used to study a single sector of the TIMES model, this paper constructs an energy technology model for CO_2 emission reduction in the power industry based on predictions of future economic and social development in China, coupled with modules of demand forecasting and emission analysis. Combined with the power industry's development attributes and characteristics of CO_2 emission control technologies, various simulation prediction and scenario analysis methods are integrated to systematically study the path of China's power industry to achieve CO_2 emission reduction through carbon tax policy.

2.2. Model Structure. The TIMES model of CO_2 emission reduction in the power industry constructed in this paper is shown in Figure 1, and the flowchart of this model is shown in Figure 2. The model mainly includes four parts: energy supply module, energy system module, energy demand module, and CO_2 emission module. The energy supply module mainly includes the supply of fossil energy (such as coal, oil, and natural gas) and nonfossil energy (such as biomass, nuclear energy, water, wind, and solar energy). The energy system module mainly includes traditional power generation technologies such as supercritical, ultrasupercritical, and IGCC (Integrated Gasification Combined Cycle), as well as new energy power generation technologies such as nuclear power, hydropower, wind power, and solar power. The energy demand module divides the terminal department into four parts: agriculture, industry, construction, and transportation. The CO_2 emission module includes two parts: CO_2 emission characteristics and potential analysis, as well as CO_2 emission reduction cost analysis.

The optimization goal of the model is to minimize the total cost of energy system in the planning period (2020–2050) under the given requirements and constraints. The objective function is shown in

$$\mathrm{OBJ}(z) = \sum_{t\in \mathrm{Years}} (1+\alpha)^{\mathrm{R-t}} \times \mathrm{ANNC}(t) - \mathrm{SALV}(z), \tag{1}$$

where OBJ(z) is the total system cost (yuan); α is the discount rate (%), which is 5% in this model; Years is the time period; R is the target year of discount; ANNC (t) is the technical cost of year t (yuan); and SALV is the salvage value of the assets (yuan).

The calculation of technical cost ANNC (t) is shown in formula (2).

$$\begin{aligned}\mathrm{ANNCY}(t) = {}& \mathrm{INVC}(t) + \mathrm{INVT}(t) + \mathrm{INVD}(t) + \mathrm{FIXC}(t) + \mathrm{FIXT}(t) \\ & + \mathrm{VARC}(t) + \mathrm{ELASTC}(t) - \mathrm{LATER}(t),\end{aligned} \tag{2}$$

where INVC is the investment cost (yuan); INVT is the tax and subsidy (yuan); INRD is the demolition cost (yuan); FIXC is the fixed operation and maintenance (O&M) cost

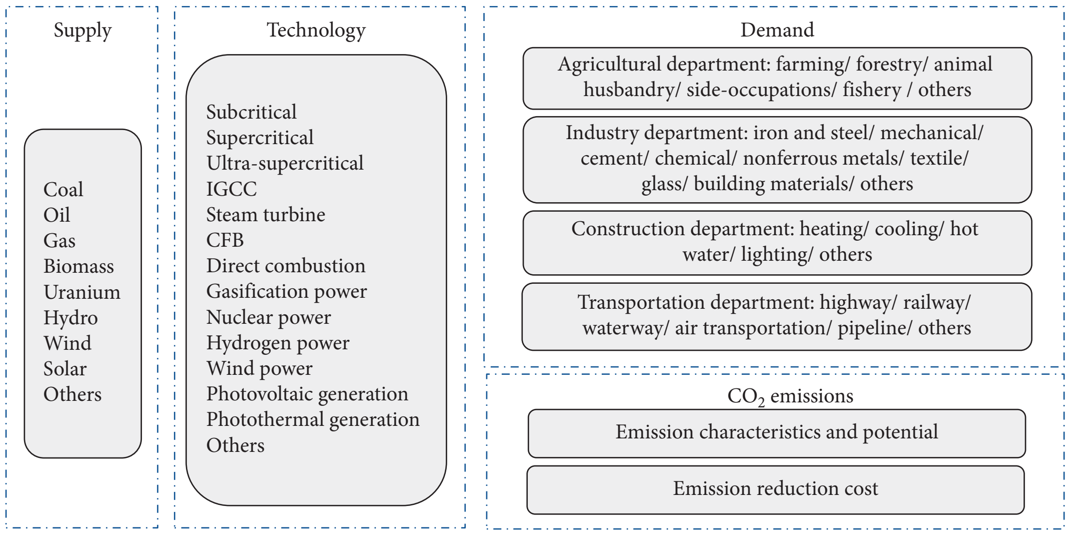

Figure 1: TIMES model of CO_2 emission reduction in China's power industry.

(yuan); FIXT is the tax and subsidy related to the fixed O&M (yuan); VARC is the variable annual O&M cost (yuan); ELASTC is the cost of demand change caused by price elasticity (yuan); and LATER is the cost of recycling (yuan).

According to the IPCC report, the CO_2 emissions of the power industry are the sum of the CO_2 emissions generated by the consumption of various fossil energy sources, as shown in formula (3) [32].

$$O_t = \sum_{m=1}^{3} O_{mt} = \sum_{m=1}^{3} E_{mt} \cdot \mathrm{NCV}_m \cdot \mathrm{CEF}_m \cdot \mathrm{COF}_m \cdot \frac{44}{12}, \quad (3)$$

where O_{mt} is the total CO_2 emissions of China's power system (10^4 t); m is the different types of primary energy (including coal, oil, natural gas, biomass, hydro, nuclear, wind, and solar); E_{mt} is the energy consumption volume (10^4 t or $10^8\,\mathrm{m}^3$); NCV_m is the net calorific value of the corresponding energy type—this article uses the average low calorific value of each energy type provided in the China Energy Statistical Yearbook (kJ/kg); CEF_m is the carbon emissions coefficient of different kinds of energy provided by IPCC; and COF_m is the carbon oxidation factor, of which coal is 0.99 and the remaining energy types are 1.

The emission reduction cost analysis process studies the corresponding unit emission reduction cost according to the obtained CO_2 emission reduction results in different scenarios, the corresponding energy consumption structure, and the advanced level of emission reduction technology. The total cost consists of three parts: average annual fixed investment cost, operating cost, and fuel cost, as shown in

$$\mathrm{TC} = \sum_{(l,p)} \left[C_{l,p} \cdot r_{l,p} + g^0_{l,p} \cdot X_{l,p} + \sum_k \left(g_k E_{k,l,p}' \right) \cdot X_{l,p} \right],$$
$$C_{l,p} = B_{l,p} \frac{\alpha (1+\alpha)^{T_{l,p}}}{(1+\alpha)^{T_{l,p}}}, \quad (4)$$

where TC is the total cost (10^8 yuan); $C_{l,p}, r_{l,p}, g^0_{l,p}, X_{l,p}, B_{l,p}, T_{l,p}$ are the average annual fixed investment cost (yuan/kW), installed capacity (10^8 kW), operating cost [yuan/(kW·a)], operating capacity (10^8 kW), initial investment cost (yuan/kW), and life (years) of facilities using l-type power generation technology and equipped with p-type control technology, respectively; α is the discount rate (%); g_k is the price of k fuel (calculated by standard coal) (yuan/t); $E_{k,l,p}'$ is the amount of fuel k consumed by facilities using l-type power generation technology and equipped with p-type control technology (calculated by standard coal) (10^8 t).

2.3. Assumptions. The model constructed in this paper takes 2015 as the research base year, and the planning period is 2020–2050. Since 2020, every 5 years is a period, that is, 2020, 2025, 2030, . . ., 2050 are the milestone years. Combined with the existing planning and future prediction [33, 34], scenario simulation is made for the development of power industry in the future. The driving factors of economic development mainly include population, urbanization rate, GDP growth rate, and industrial structure (the ratio of the primary, secondary, and tertiary industries). Therefore, the basic assumption results of the model are shown in Table 1.

It is found that during the period of 2015–2050, the total population shows a trend of increasing firstly, reaching a peak value in 2035 (1459 million), and then slowly decreasing to 1415 million in 2050. The urbanization rate continues to increase, reaching 75.9% by 2050, and the corresponding urban population will be 1074 million. While the GDP growth rate is slowly decreasing, the industrial structure has changed significantly. Compared with the base year, in 2050, the ratio of the secondary industry will decrease by 12.1%, and the ratio of the tertiary industry will increase by 17.6%. This change shows that as China's industrialization process gradually enters a stable period, the focus of energy consumption will gradually shift from industry to service industries including construction and

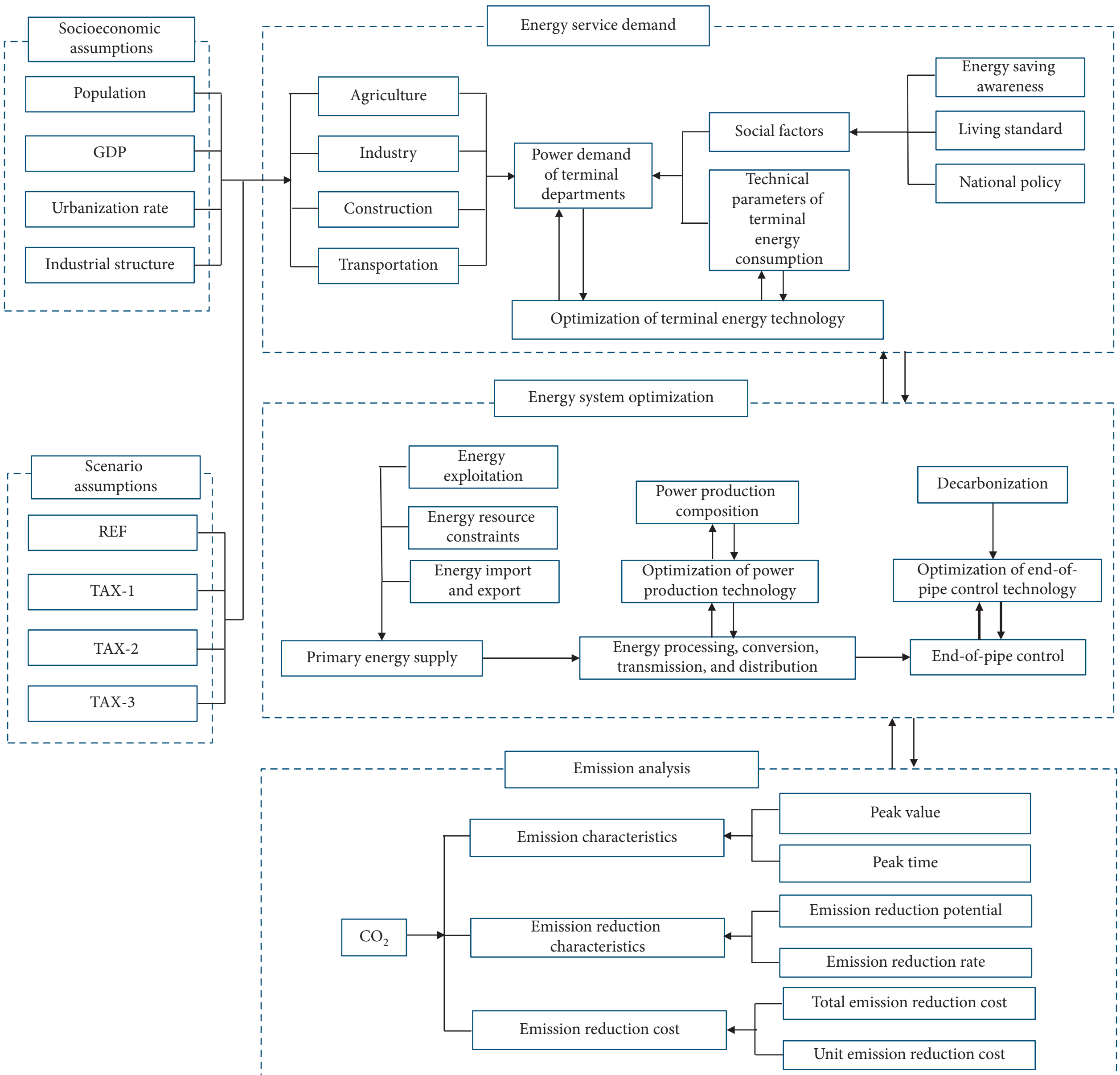

Figure 2: Flowchart of the proposed method.

Table 1: Basic assumptions of the model.

Year	Total population (million)	Urban population (million)	Rural population (million)	Urbanization rate (%)	GDP growth rate (%)	Ratio of primary industry (%)	Ratio of secondary industry (%)	Ratio of tertiary industry (%)
2015	1400	774	626	55.3	7.0	9.8	42.3	47.9
2020	1421	838	583	59.0	6.2	6.9	40.7	47.9
2025	1442	898	544	62.3	5.6	6.3	38.1	55.6
2030	1455	963	492	66.2	4.5	5.9	36.7	57.4
2035	1459	1014	445	69.5	4.5	5.6	35.0	59.4
2040	1452	1037	415	71.4	4.5	5.2	33.4	61.4
2045	1432	1048	384	73.2	4.0	4.9	31.9	63.2
2050	1415	1074	341	75.9	3.5	4.3	30.2	65.5

transportation. This adjustment of industrial structure can not only reduce the energy consumption per unit of GDP, but also lead to the improvement of technological energy-saving level, further illustrating that the adjustment of the energy structure and technological upgrading can play important roles in the process of CO_2 emission reduction.

2.4. Scenarios. In order to obtain the optimal carbon tax level, as well as the corresponding optimal policy measures and technology combinations, four scenarios are set up in this paper, including the reference scenario and three carbon tax scenarios with different carbon tax levels.

2.4.1. Reference (REF) Scenario. The impact of CO_2 on the development of power industry is not considered. No new technology is introduced and improved. The power system develops at the original level without any change in the energy structure and emission reduction technology, which still relies on traditional coal power generation.

2.4.2. Carbon Tax Scenarios. It is divided into three scenarios, the low-carbon tax scenario (TAX-1 scenario), the medium carbon tax scenario (TAX-2 scenario), and the high-carbon tax scenario (TAX-3 scenario). As can be seen from the foregoing, the CO_2 emissions from fossil fuel combustion account for the majority of China's total greenhouse gas emissions, and the emissions are relatively centralized and easy to calculate, so it is more in line with China's current national conditions to adopt the estimated CO_2 emissions as the basis of tax calculation and levy in the way of quantity-based collection [35]. Therefore, this paper assumes the carbon tax collecting on CO_2 emissions from fossil fuel combustion. Based on the REF scenario, it is assumed that carbon tax will be levied on the power industry from 2020. The carbon tax rates set in this paper refer to the Asian Energy Model Forum and related literature [36–38], as shown in Table 2. Among them, the carbon tax set in TAX-1, TAX-2, and TAX-3 scenarios has different change rules. The unit of carbon tax rate infer to CNY per tons of CO_2. In 2020, the carbon tax is set at 70 yuan/t, 210 yuan/t, and 350 yuan/t, respectively; then it will increase at different growth rates in different periods, finally reaching 301 yuan/t, 910 yuan/t, and 1512 yuan/t, respectively, in 2050.

Table 2: Carbon tax rates set under different scenarios (yuan/t).

Carbon tax scenarios	Year						
	2020	2025	2030	2035	2040	2045	2050
TAX-1	70	91	112	151	189	245	301
TAX-2	210	277	343	452	560	735	910
TAX-3	350	459	567	749	931	1222	1512

3. Results and Discussion

3.1. Power Consumption Demand. Parameters such as population, GDP growth rate, urbanization rate, and industrial structure are important factors to determine the national power consumption demand. Therefore, according to the basic assumptions of China's future economic and social development obtained above, China's power demand during 2015–2050 can be obtained, as shown in Table 3.

It is found that during this period, China's national power demand shows an overall upward trend and develops at a high level. In 2050, the demand (17075 billion kW·h) is 2.81 times that in 2015 (6080 billion kW·h). The annual average growth rate is 16%, far higher than the GDP growth rate in the same period, but the growth rate is decreasing year by year. This is because there is a close correlation between the process of national economic development and the intensity of power demand. It can be seen from the above that with the continuous promotion of urbanization, obvious industrial structure and rigid energy demand are the most important development characteristics, thus maintaining a high demand for power consumption. As a result, the growth rate of national and per capita power demand will remain above 10% in 2020–2040. With the completion of China's industrialization, the economic structure has been transformed; the proportion of the tertiary industry has increased, and the heavy industry, especially the high-energy-consuming industry, has gradually withdrawn. The intensity of power consumption has also declined, leading to a slowdown in the growth of power demand. At the same time, with the development of productivity and the improvement of living standards, the overall demand for electricity is gradually increasing. However, the promotion of energy-saving technology and the popularization of energy-saving awareness lead to the gradual slowdown in the growth rate of per capita power demand. Therefore, in 2050, the corresponding growth rate of China's overall and per capita power demand will be significantly reduced to 6% and 7%, respectively.

The power demand of each terminal department is shown in Figure 3. With the development of economy, the overall power consumption of the terminal departments will be improved to some extent in the future. The focus of power demand will gradually shift from industry to transportation and construction. Among them, the proportion of power demand in the industrial department has declined significantly, from 71.90% in 2015 to 36.24% in 2050. The reason is that, on the one hand, the productivity and efficiency have been increased, and energy consumption has been greatly reduced; on the other hand, the industrial structure has changed significantly and the tertiary industry and capital-intensive and technology-intensive industries have developed rapidly. The proportion of transportation department will increase from 13.84% in 2015 to 31.81% in 2050, mainly due to the energy utilization and the extensive application of electric vehicle technology. The proportion of power demand in the construction department has increased significantly, reaching 30.58% in 2050. On the one hand, the rate of home appliance ownership and penetration has increased year by year; on the other hand, due to the increase of urbanization rate, urban population and urban scale have been increased, leading to the power demand of corresponding infrastructure greatly increased. At the same time, the growth rate of electricity demand in the construction department will reach the highest value of 50.33% from 2025 to 2030. It can be seen from the above that this is due to the largest growth rate of urbanization and the rigid demand for power during this period. In addition, the proportion and growth rate of power demand in the agricultural department have been declining. This is mainly because with the development of economy and society, the scale effect based on

Table 3: Characteristics of power demand in China.

Year	National power demand (billion kW·h)	Growth rate of national power demand (%)	Per capita power demand (kW·h)	Growth rate of per capita power demand (%)
2015	6080	—	4342	—
2020	7661	26	5391	24
2025	9576	25	6640	23
2030	11491	20	7897	19
2035	13560	18	9293	18
2040	14916	10	10272	11
2045	16109	8	11249	10
2050	17075	6	12067	7

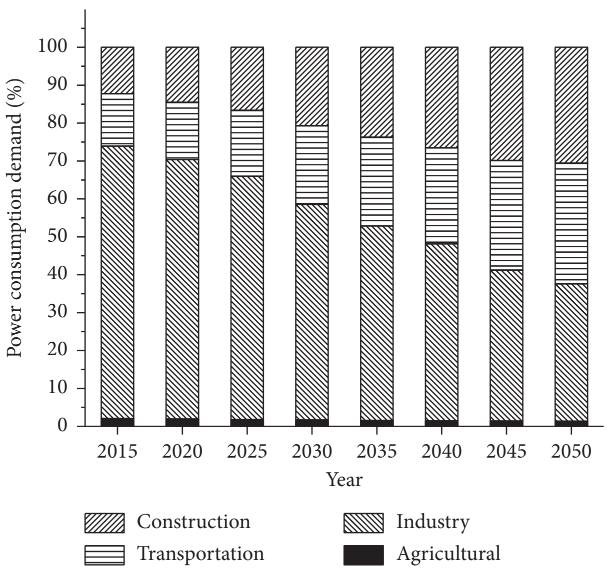

Figure 3: Power consumption demand of terminal departments.

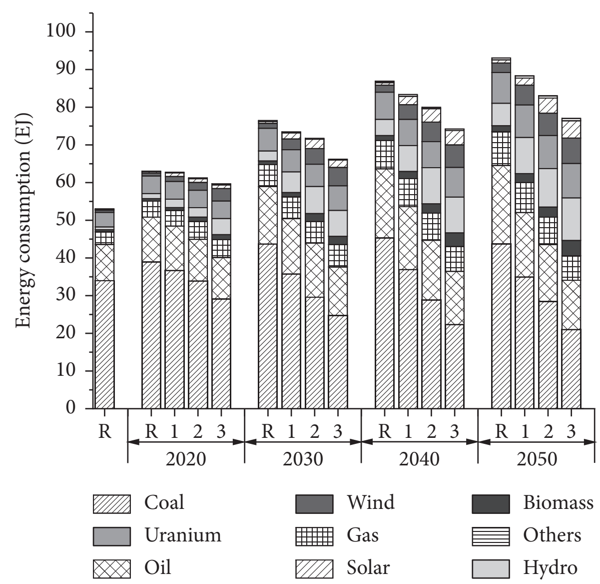

Figure 4: Primary energy consumption and composition.

the agricultural economy will show the trend of accelerating expansion. While the efficiency of electricity consumption is improving, the power demand for agricultural is greatly reduced.

3.2. Primary Energy Consumption and Composition. The simulation results of primary energy consumption and composition under the four scenarios are shown in Figure 4.

Under the REF scenario, the total primary energy consumption will increase from 53.13 EJ in the base year to 63.17 EJ, 76.61 EJ, and 87.07 EJ in 2020, 2030, and 2040, respectively. It will reach 93.24 EJ in 2050, which is a 75% increase compared with the base year, and the proportion of fossil energy will still be as high as 78.98%. This will put great pressure on the energy supply and CO_2 emission control of China's power industry, so it is necessary to reduce the total energy consumption and adjust the energy consumption structure.

Under the scenarios of TAX-1, TAX-2, and TAX-3, the primary energy consumption of China's power industry will be significantly decreased compared to the REF scenario. The total energy consumption in 2030 will reach 73.58 EJ, 71.86 EJ, and 66.34 EJ, respectively. In 2050 it will be further decreased to 88.48 EJ, 83.21 EJ, and 77.19 EJ, respectively, compared with the REF scenario, the corresponding decrease is 5%, 11%, and 17%. This is mainly due to the adjustment of energy structure, as well as the use and upgrade of energy-saving technologies, such as energy-saving appliances and wall insulation technology. At the same time, the composition of primary energy consumption has a large degree of change. In 2050, under the three carbon tax scenarios, the proportion of fossil energy consumption to total consumption will be 67.97%, 61.20%, and 52.68%, respectively. Compared with the REF scenario (the corresponding proportion is 78.98%), the consumption of coal, oil, and natural gas will be greatly reduced, while the renewable energy is further developed. Among them, under the TAX-3 scenario in 2050, the proportion of hydropower, nuclear energy, wind energy, solar energy, and biomass energy will increase from 1.42% in base year to 14.66%, 7.27% to 11.87%, 1.03% to 8.71%, 0.47% to 5.97%, and 1.03% to 5.28%, respectively.

Through the price mechanism of the market, the collection of carbon tax makes power producers turn to clean energy and low-carbon products to achieve the purpose of emission reduction. It has a suppressive effect on high-energy consumption technologies and a promotion effect on low-energy consumption technologies, resulting in a tumultuous change in the consumption of energy products. The emission reduction effect of carbon tax is positively related to the price elasticity of energy demand and the substitution of energy products. Related technologies will be promoted, with considerable benefits of the extension effect.

3.3. CO_2 Emissions and Emission Reduction Characteristics. The CO_2 emissions, emission reduction potential, and emission reduction rate of the power industry in different scenarios are shown in Figure 5 and Table 4. The calculation of emission reduction potential and emission reduction rate is shown in formulas (5) and (6), respectively.

$$E_{qt} = E_{Rt} - E_{Tt}, \tag{5}$$

where E_{qt} is the emission reduction potential of year t under a carbon tax scenario (Gt); E_{Rt} is the CO_2 emissions of year t under the REF scenario (Gt); and E_{Tt} is the CO_2 emissions of the carbon tax scenario in the same period (Gt).

$$E_{\eta} = \frac{E_{qt}}{E_{Rt}}, \tag{6}$$

where E_{η} is the emission reduction rate (%).

Under the REF scenario, the CO_2 emissions of the power industry will be increasing year by year, reaching a peak value of 5.52 Gt in 2050, which is an increase of 44% over the base year. According to the obtained CO_2 emissions, it can be found that the power industry will not be able to achieve the CO_2 emission reduction targets in all stages if the existing structure and technology are still maintained without taking corresponding adjustment measures.

Compared with the REF scenario, under the TAX-1, TAX-2, and TAX-3 scenarios, the corresponding CO_2 emissions increase firstly and then decrease. With the increase of carbon tax level, the emissions will reach the peak values of 4.64 Gt, 4.39 Gt, and 4.12 Gt in 2040, 2035, and 2030, respectively and then decrease year by year, reaching 4.54 Gt, 4.02 Gt, and 3.79 Gt, respectively, in 2050. The corresponding emission reduction potential will be 0.98 Gt, 1.50 Gt, and 1.73 Gt, respectively. At the same time, combined with the CO_2 emission reduction rate in 2050, it will be close to 30% under the TAX-2 scenario, while under the TAX-3 scenario, although the carbon tax has increased significantly, it will only increase by 4%, which is 31.34%. The improvement degree of emission reduction effect is not obvious enough, which cannot show a high correlation with the corresponding growth degree of carbon tax.

In addition, the CO_2 emission reduction characteristics of the power industry in different scenarios are shown in Figure 6. The calculation of emission reduction is shown

$$E_{ri} = E_{oi} - E_{pi}, \tag{7}$$

where E_{ri} is the CO_2 emission reduction (Gt); E_{oi} is the CO_2 emissions under uncontrolled conditions (Gt); and E_{pi} is the actual CO_2 emissions during the same period (Mt).

Under different carbon tax scenarios, with the adjustment of energy consumption structure and level

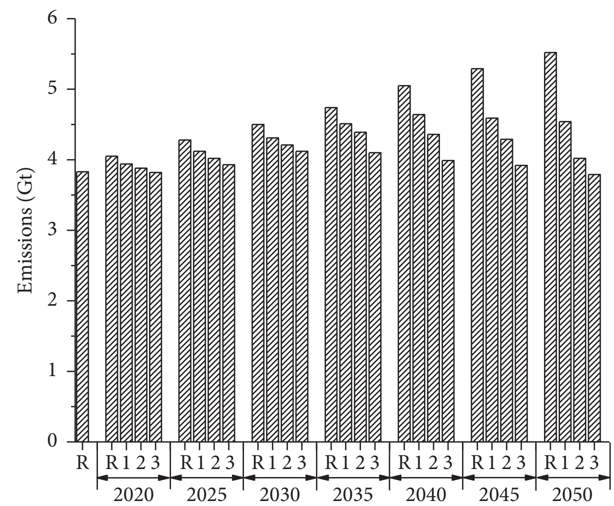

Figure 5: CO_2 emissions of power industry.

improvement of technology in the power industry, CO_2 emission reduction shows an increasing trend. When 2050, the emission reduction corresponding to the three scenarios will be 1.49 Gt, 2.01 Gt, and 2.24 Gt, respectively, which will increase by 0.87 Gt, 1.33 Gt, and 1.50 Gt compared to 2020. In the REF scenario, the emission reduction in 2050 will be only 0.51 Gt.

In summary, carbon tax in China's power industry can lead enterprises to actively reduce CO_2 emissions. In this process, the collection of carbon tax can increase the production cost of high-carbon emission enterprises. Therefore, it is necessary to develop the emission reduction technologies and adopt the low-carbon energy sources to achieve low-carbon production and energy structure adjustment.

3.4. CO_2 Emission Reduction Cost. In the power industry, the collection of carbon tax will have a great impact on the emission reduction cost. The transformation of production mode as well as the transformation and upgrading of power production can be guided and realized by the level of emission reduction cost [39]. Therefore, a reasonable level of carbon tax can significantly promote CO_2 emission reduction and structural optimization, while substantially reducing its impact on the economy. Combined with the above results, the cost of emission reduction under the four scenarios is further analyzed to obtain a more effective and conducive collection level for carbon tax promotion. The results are shown in Table 5, where ΔC is the cost of CO_2 emission reduction (billion yuan); ΔE is the CO_2 emission reduction (Gt); and $\Delta C/E$ is the unit emission reduction cost of CO_2 (billion yuan/Gt).

Under the REF scenario, from 2020 to 2050, as can be seen from the foregoing, the power industry's dependence on coal has not changed significantly, and the emission reduction technology has not been introduced and upgraded. Therefore, the unit emission reduction cost of CO_2 fluctuates slightly, maintaining between 6.04×10^3 and 6.63×10^3 billion yuan/Gt. Since the lifecycle of equipment

Table 4: Emission reduction potential and emission reduction rate of power industry.

Carbon tax scenarios	2020		2025		2030		2035		2040		2045		2050	
	E_q	E_η	E_q	E_η	E_q	E_η	E_q	E_η	E_q	E_η	E_q	E_η	E_q	E_η
TAX-1	0.11	2.72	0.16	3.74	0.19	4.22	0.23	4.85	0.41	8.12	0.70	13.23	0.98	17.75
TAX-2	0.17	4.20	0.26	6.07	0.29	6.44	0.35	7.38	0.69	13.66	1.00	18.90	1.50	27.17
TAX-3	0.23	5.68	0.35	8.18	0.38	8.44	0.64	13.50	1.06	20.99	1.37	25.90	1.73	31.34

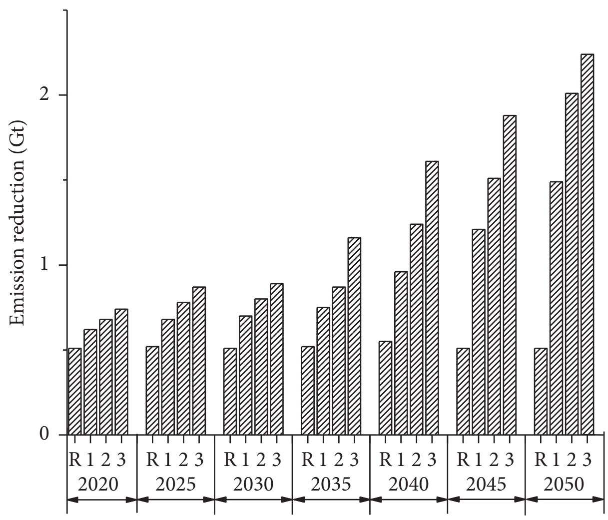

Figure 6: CO_2 emission reduction characteristics of power industry.

Table 5: CO_2 emission reduction cost of power industry.

Year	Item	REF	TAX-1	TAX-2	TAX-3
	ΔC	$3.28E+03$	$7.14E+03$	$1.11E+04$	$2.26E+04$
2020	ΔE	0.51	0.62	0.68	0.74
	$\Delta C/E$	$6.44E+03$	$1.15E+04$	$1.63E+04$	$3.06E+04$
	ΔC	$3.44E+03$	$9.13E+03$	$1.53E+04$	$3.37E+04$
2025	ΔE	0.52	0.68	0.78	0.87
	$\Delta C/E$	$6.61E+03$	$1.34E+04$	$1.96E+04$	$3.88E+04$
	ΔC	$3.33E+03$	$1.03E+04$	$1.94E+04$	$4.22E+04$
2030	ΔE	$5.10E-01$	$7.00E-01$	$8.00E-01$	$8.90E-01$
	$\Delta C/E$	$6.52E+03$	$1.48E+04$	$2.42E+04$	$4.74E+04$
	ΔC	$3.45E+03$	$1.29E+04$	$2.60E+04$	$4.17E+04$
2035	ΔE	$5.20E-01$	$7.50E-01$	$8.70E-01$	$1.16E+00$
	$\Delta C/E$	$6.63E+03$	$1.72E+04$	$2.99E+04$	$3.60E+04$
	ΔC	$3.49E+03$	$1.87E+04$	$2.61E+04$	$3.53E+04$
2040	ΔE	$5.50E-01$	$9.60E-01$	$1.24E+00$	$1.61E+00$
	$\Delta C/E$	$6.34E+03$	$1.95E+04$	$2.11E+04$	$2.19E+04$
	ΔC	$3.19E+03$	$2.64E+04$	$2.56E+04$	$2.84E+04$
2045	ΔE	$5.10E-01$	$1.21E+00$	$1.51E+00$	$1.88E+00$
	$\Delta C/E$	$6.26E+03$	$2.18E+04$	$1.70E+04$	$1.51E+04$
	ΔC	$3.08E+03$	$2.62E+04$	$2.02E+04$	$1.81E+04$
2050	ΔE	$5.10E-01$	$1.49E+00$	$2.01E+00$	$2.24E+00$
	$\Delta C/E$	$6.04E+03$	$1.76E+04$	$1.01E+04$	$8.10E+03$

and process is basically around 20 years, the unit emission reduction cost will increase slightly during 2030 and 2035.

Under the TAX-1, TAX-2, and TAX-3 scenarios, the unit emission reduction cost of CO_2 increases firstly and then decreases. Due to different levels of carbon tax, in the short term, in order to reduce carbon emissions and avoid the pressure of carbon tax, the emission reduction technology and production mode of power industry will be greatly changed, resulting in different degrees of increase in the cost of emission reduction. Therefore, in 2020, the unit emission reduction cost of the three scenarios will be 1.15×10^4 billion yuan/Gt, 1.63×10^4 billion yuan/Gt, and 3.06×10^4 billion yuan/Gt, respectively, among which the lower carbon tax scenarios (TAX-1, TAX-2) have lower initial unit emission reduction cost than the higher carbon tax collection scenario (TAX-3). The unit emission reduction cost corresponding to the three carbon tax scenarios will peak in 2045, 2035, and 2030, respectively, with the values of 2.18×10^4 billion yuan/Gt, 2.99×10^4 billion yuan/Gt, 4.74×10^4 billion yuan/Gt, respectively. After that, it will continue to decline, decreasing to 1.76×10^4 billion yuan/Gt, 1.01×10^4 billion yuan/Gt, and 8.10×10^3 billion yuan/Gt, respectively, in 2050. At this time, compared with the TAX-1 scenario, the unit emission reduction costs of the TAX-2 and TAX-3 scenarios are lower. From a long-term perspective (after 2050), a higher carbon tax level benefits the reduction of unit emission reduction cost. This is mainly because under the pressure of high-carbon tax level, enterprises passively accept the substantial increase of emission reduction cost in the initial period. The optimal solution with lower cost will be actively sought. The production mode gradually changes based on maintaining power production, such as using new energy power generation technology with lower CO_2 emissions and optimizing emission reduction technologies. CO_2 emissions can be reduced to offset the loss caused by carbon tax, with the energy consumption structure improved. In addition, the average unit emission reduction cost under the TAX-1, TAX-2, and TAX-3 scenarios during 2020–2050 will be 1.65×10^4 billion yuan/Gt, 1.97×10^4 billion yuan/Gt, and 2.83×10^4 billion yuan/Gt, respectively, which is 4 times, 5 times, and 9 times that of the REF scenario, respectively.

3.5. Impact of Carbon Tax on the Macroeconomy of the Power Industry

It can be seen from the above that carbon tax can force the green transformation of the power industry, but as a "double-edged sword," it has a wide-ranging and far-reaching impact, involving many aspects of society, economy, and people's life. Therefore, the carbon tax should consider not only the impact on the environment, but also its economic effect. Like other types of taxes, carbon tax will also change the price signal, making resources deviate from the optimal allocation under the reference scheme, resulting in the loss of GDP [40].

The impact of different carbon tax levels on the macroeconomy of the power industry is shown in Table 6. In

Table 6: Impact of different carbon tax levels on the macroeconomy of the power industry.

Carbon tax scenarios	GDP_η				TAX_η			
	2020	2030	2040	2050	2020	2030	2040	2050
TAX-1	0.08	0.07	0.12	0.19	34.8	61.2	69.7	95.5
TAX-2	0.05	0.10	0.18	0.28	89.3	61.8	74.3	97.1
TAX-3	0.13	0.27	0.60	0.72	44.9	31.7	35.2	43.8

order to quantify the additional effect of carbon tax on GDP, based on the CO_2 emission reduction characteristics obtained previously, this paper proposes the "carbon tax elasticity coefficient" index TAX_η, which is shown in formula (8). While ensuring the emission reduction effect, the larger the value, the greater the elasticity of the corresponding carbon tax to national economy and the smaller the GDP loss. The optimal carbon tax can be obtained through the calculation of this index. It can effectively promote the decoupling between the emission reduction of CO_2 and the growth of national economy and then provide more space for emission reduction, while producing additional effects such as reducing production energy consumption and preventing greenhouse effect.

$$TAX_\eta = \frac{E_\eta}{GDP_\eta}, \tag{8}$$

where TAX_η is the carbon tax elasticity coefficient and GDP_η is the GDP loss rate in the same period (%).

It is found that the GDP loss rate in 2040 will be as high as 0.60% in TAX-3 scenario, which is much higher than the other scenarios. If the tail effect of the model is considered, the GDP loss rate in 2050 should exceed the calculated value of 0.72%. In the other scenarios, the peak of GDP loss rate in each year is only 0.28%. It can be seen from the above that under the TAX-3 scenario, although the carbon tax level has increased significantly, the emission reduction rate has only increased by 4% compared with the TAX-2 scenario. Its emission reduction effect has not improved significantly, with the dramatically increased resulting GDP loss. In the TAX-2 scenario, TAX_η is the highest, indicating that it has the most elastic impact on the national economy and the smallest GDP loss while ensuring the emission reduction effect. In addition, comprehensively considering the cost of CO_2 emission reduction obtained above, the CO_2 emission reduction cost in the TAX-3 scenario is as high as 9 times of that in the REF scenario. Therefore, in the long run, TAX-2 can better meet the requirements of emission reduction effect and cost in the power industry at the same time, which performs best in the four scenarios. The carbon tax set in this scenario can be used as an effective environmental economic policy tool to reduce energy consumption and CO_2 emissions, as well as changing the energy consumption structure. Although the economic growth will be restrained in the short term, it is beneficial to the healthy development of the whole economy in the medium and long term.

From the perspective of eliminating backward production capacity, carbon tax will increase the development cost of power generation enterprises; but on the contrary, these increased production costs can prevent some power plants from blindly expanding production capacity, which promotes the technological innovation and upgrading of the power industry. As a good policy signal, carbon tax can effectively control the development of high-energy consumption technologies in power industry. In the whole world, carbon tax can promote the sustainable development of the power industry and enhance the international competitiveness of the country to a certain extent.

4. Conclusions

With the development of economy and society in the future, China's power consumption demand and the primary energy consumption of the power industry will all show rapid growth. Power production still heavily dependents on fossil energy, which will far exceed the supply capacity of coal production, causing great pressure on China's economic development and ecological environment. Under the REF scenario, the CO_2 emissions of the power industry will be increasing year by year, reaching a peak value in 2050.

Carbon tax will have an important impact on the primary energy supply structure of China's power industry. Under the three TAX scenarios, in 2050, when comparing with the REF scenario, the primary energy consumption of the power industry will decrease, and its composition will change to a large extent. The proportion of fossil energy consumption in total consumption will be reduced, while renewable energy has developed to different degrees. With the gradual increase of carbon tax level, the CO_2 emissions in 2050 will be reduced to varying degrees under the TAX scenarios. The corresponding emission reduction potential proves the effectiveness of carbon tax on reducing CO_2 emissions.

The medium carbon tax level (TAX-2) set in this paper can better meet the requirements of CO_2 emission reduction effect and cost in the power industry. It has the most elastic impact on the national economy and the smallest GDP loss while ensuring the emission reduction effect, which can be used as an effective environmental economic policy tool.

Combined with the research results obtained above, a low-carbon development policy is proposed to realize the CO_2 emission reduction of China's power industry: (1) save primary energy and improve energy efficiency; (2) make full use of renewable energy and optimize energy structure; (3) integrate CO_2 control and economic transformation; and (4) improve carbon tax system and pollution management mechanism.

To further enhance the practical application value of the research, the fiscal immunity and transfer payment will be studied based on carbon tax in the future, in combination with "top-down" energy economic models such as CGE model.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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