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Research on the applicability and impact of CO_2 emission reduction policies on China's steel industry

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Abstract

Purpose – Environmental problems such as CO_2 (Carbon Dioxide) emissions have seriously affected the development of the steel industry, which has urged the industry to adopt a more effective emission reduction policy. This paper aims to analyze the impact of various CO_2 emission reduction policies combinations on the economic benefits and environmental changes of the steel industry and to determine the scope of application.

Design/methodology/approach – To compare the impact and applicable implementation conditions, a production decision game model that incorporates these two policies has been constructed. Short-,

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Data availability: The statistics in this paper are from the China Statistical Yearbook, China Industrial Statistical Yearbook, China Energy Statistical Yearbook, China Steel Yearbook and the statistical yearbooks of various provinces. All data are publicly available on the website and can also be purchased. The relevant results of this paper are calculated on the basis of these public data, and these statistical data and books have been marked and quoted in the paper.

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medium- and long-term constraints are set on the emission reduction indicators and the indicators' changes under various scenarios are compared.

Findings – In the case of a single emission reduction policy, the carbon trading (CT) mechanism is better than the carbon tax mechanism. The mixed carbon trading mechanism is superior to the mixed carbon tax mechanism in terms of total output and subsidies, but worse in terms of overall social welfare, producer surplus and macro losses.

Originality/value – This paper constructs multiple emission reduction and production backgrounds and discusses the impact of the comprehensive implementation of these policies, which is practically absent in previous studies. It is in line with the current industrial policy for stable production and environmental protection and also provides a reference for the formulation of detailed policies in the future.

Keywords Applicability and impact, Carbon tax mechanism, Carbon trading mechanism, China's steel industry, CO_2 emission reduction policies, dynamic game modeling

Paper type Research paper

1. Introduction

As an important manufacturing sector in China, the Chinese steel industry is well known internationally for its achievements; however, it also faces many problems to be solved. In recent years, environmental and climate problems (Yang *et al.*, 2020a, 2020b, 2021) have occurred frequently, which has gradually increased the pressure on the steel industry to make strides in energy conservation and emissions reduction. The implementation of reasonable CO_2 emission reduction policies can achieve the purpose of large-scale reduction of CO_2 emissions, and also help alleviate the financial pressure on steel industry enterprises. Carbon tax policy and carbon trading policy are two policy tools that represent economic incentives to improve emission reduction. At the end of 2020, the Ministry of Industry and Information Technology of China issued the "Guiding Opinions on Promoting the High-Quality Development of the Iron and Steel Industry (Draft for Solicitation of Comments)." In this document, it is clearly stated that it is necessary to gradually establish a production restriction mechanism based on carbon emissions, promote the implementation of market-based trading policies for carbon taxes and carbon emissions in the steel industry, and implement differentiated industrial policies for companies with different levels of environmental protection governance. Therefore, research on carbon tax policy and carbon trading policy is becoming a focus for experts, scholars and policymakers.

2. Literature review

Many scholars have done a lot of pioneering work in response to China's CO_2 emissions. In terms of research methods, scholars have combined mathematics, economics and engineering models (Ning *et al.*, 2020; Song *et al.*, 2020; Zhang *et al.*, 2021; Song *et al.*, 2021) to study CO_2 emissions reduction issues. Regarding the selection of emission reduction policies, the academic community is mainly divided into the following main viewpoints.

Aviyonah and Uhlmann (2009) proposed that the carbon tax mechanism is easier to implement than the carbon trading mechanism because the carbon trading mechanism faces the challenge of setting emission reduction targets. Roberta (2009) favors the carbon tax policy because a carbon tax is easy to implement, it helps enterprises choose an optimal emission reduction path and local governments are not able to resist the carbon tax easily by implementing local protectionism. Strand (2013) found that fossil fuel importers that implement an optimal climate policy prefer carbon tax policies because they can enjoy lower fuel import prices under the carbon tax system. Xu and Mao (2019) extended the classic RBC (Real Business Cycle) model by introducing variables such as carbon tax, carbon emissions, carbon stock and human capital and found that carbon tax reform not only can reduce carbon emissions and carbon stock but also can affect human capital. Ding *et al.* (2019) developed a diffusion model of energy technology based on endogenous technology learning under bounded rationality to explore the possible impacts of different carbon tax conditions on the diffusion of energy technologies in China. Lin and Jia (2020a) constructed a dynamic recursive computable general equilibrium model and indicated that CT (carbon trading) can share the mitigation pressure from emissions trading system (ETS) coverages into non-ETS coverages. In their another research (2020b), they recommended that China could directly levy a carbon tax on energy enterprises or just increase the production tax on fossil fuels to reduce CO_2 emissions effectively.

In contrast, Jaffe and Stavins (1994) believed that carbon trading is superior to a carbon tax. They argued that the decline of the price of carbon emission rights was the result of technological innovation. Zanni *et al.* (2013) used a variety of survey methods to show that carbon trading is more easily accepted by consumers than the carbon tax. Raux *et al.* (2015) believed that carbon trading more effectively changed people's travel habits (and thus reduced carbon emissions caused by travel) than carbon taxes did. Fan *et al.* (2015) believed when energy prices fluctuate, carbon trading schemes are more effective than carbon tax schemes. Wang *et al.* (2016) believed that in the short-term, due to the higher cost of emission reduction technologies, carbon trading mechanisms are more cost-effective. Haites (2018) horizontally compared the performance of ETS and carbon tax in terms of environmental benefits, cost-effectiveness (marginal abatement costs [MACs]), economic benefits, public finances and administrative issues and found that ETS performs better than the carbon tax. Chen *et al.* (2020) found that a cap-and-trade system is more efficient to reduce emissions and to promote clean innovation than the carbon tax.

Other scholars have proposed that the two policies (carbon tax and carbon trading) should be complementary. In theory, under certain assumptions, the carbon trading mechanism and the carbon tax mechanism are equivalent. From the perspective of social welfare effects, Pizer (2002) considered that the mixed tool is more effective than a carbon tax on its own. The social welfare effect produced by a mixed policy is more effective. Lee *et al.* (2008) found that when carbon trading and carbon tax policies were implemented simultaneously, the petrochemical industry's GDP loss was small. Mandell (2008) researched the issues from the perspective of efficiency loss and believed that the effect of mixed regulation was better than that of a single policy. In China, Shi *et al.* (2013) showed that the combination of carbon tax and carbon emissions trading policies could effectively control the total amount of CO_2 emission reduction and would also have less impact on the production and operations of enterprises. Sun (2014) believed that the combination of carbon tax and carbon emissions trading policies is more in line with China's national conditions. Wei (2015) proposed that carbon trading can be compatible with carbon taxes to achieve certain relative emission reduction targets. Liu (2016) put forward the "common but differentiated" responsibility principle for environmental improvement in each region in accordance with the current economic development strategy requirements of industries and regions. CAFS Research Group (2018) suggested that based on actual national conditions and the actual needs of carbon emission reduction, China should consider the two parallel and comprehensive applications of carbon trading and carbon tax at the present stage and the next period. Zhang *et al.* (2019) explored the carbon trading price and the carbon tax rate intervals that enable the manufacturer to choose the more profitable marketing strategy and at the same time to achieve a reduction in carbon emissions to the environment. Zhao *et al.* (2020) believed that the policy mix formed by a carbon tax and carbon trading is comprehensive in terms of both price flexibility and coverage scope.

In addition, some scholars believe that in accordance with China's actual situation, phased emission reduction should be adopted. Yang (2010) compared the practical experience of foreign carbon taxes and carbon trading systems, and he argued that China should levy carbon taxes to control carbon emissions in the short-term to promote technological innovation and industrial transformation and upgrading. Fang (2012) proposed a phased emission reduction approach in China: a short-term levy of carbon taxes to promote the adjustment of the industrial structure, and a long-term program in which the carbon emission trading mechanism would eventually become the dominant mode of regulation. Wan (2012) believed that the implementation of a carbon trading policy is unavoidable, but suggested that the resulting reduction of emissions would not be obvious in the short-term. It is suggested that the introduction of a carbon tax would be conducive to the balance between carbon emissions reduction and economic development. Yu *et al.* (2014) believed that a strategy of implementing a carbon tax in the short-term and a carbon trading policy in the long-term would be in line with China's anticipated future situation. Zhang *et al.* (2019) believed that the stepped carbon tax should be actively promoted, as a significant role in promoting carbon emission reductions, but the interests of the emission reduction entities should be considered as well. Zou *et al.* (2020) found that when the emission reduction cost coefficient of manufacturers is relatively low, increasing carbon tax and the carbon emission permits price can effectively promote the emission reduction behavior of manufacturers. However, when the emission reduction cost coefficient of the manufacturers is quite high, increasing carbon tax and carbon emission permits price cannot effectively promote the emission reduction behavior.

Through the literature review, it can be found that scholars have not reached a consensus on the selection and application of carbon tax and carbon trading policies. In terms of industrial applications, as China has not yet implemented these two emission reduction policies on a large scale, more theoretical research is being focused on the national level and the overall industry level. The impact of these policies on the production level and economic profit of individual enterprises and of the steel industry as a whole, as well as their suitability for the actual situation of the steel industry, has not been clearly determined. However, given the increasing pressure on China's industrial sectors to reduce carbon emissions, these two policies will inevitably be applied to various industrial sectors in China. For the steel industry, in the next 10 years or even longer, how should the industry choose a reasonable emission reduction policy? The question will be the focus of this paper.

In the previous research, Duan *et al.* (2017) used game theory to explore the application of carbon tax policy in the steel industry. As preliminary research, it brings a more complete idea to the model construction of this research. That is, under the framework of game theory, to consider and integrate the carbon tax mechanism, the carbon trading mechanism, production subsidies, CCS (carbon capture and sequestration) and the external loss of CO_2 into the emissions reduction mechanism when building a two-stage dynamic game model. By calculating and comparing several overall economic indicators and environmental consequences of the steel industry – including total output, social welfare, producer surplus and macro-environmental losses – in the multiple emission reduction scenarios, the application scope and the effect of these two emission reduction policies can be obtained in this paper. These are also the core goal and main research propositions.

The remainder of this paper is organized as follows. In Section 3, this paper establishes a production decision game model under the carbon tax policy and carbon trading policy, which examines multiple emission scenarios and multiple carbon emissions benchmarks. In Section 4, based on accounting data and statistical analysis, we present our results in detail. Section 5 discusses the reasons for the change trend of the results. Section 6 provides conclusions and policy recommendations for China's steel industry.

3. Methods

3.1 Notations and explanations

According to the traditional Chinese geographical division method and references (Duan *et al.*, 2019; Duan *et al.*, 2020), the main research focus of this paper encompasses the government and six regions1. The regional steel industry data are regarded as a steel enterprise entity. The government emissions reduction policy is a double game problem. This paper adopts the inverse method in solving the two-stage game problem. On the basis of previous research, we integrate the parameters required in this paper, which are shown in Table 1.

3.2 Construction and solution of a dynamic game model for steel industry production decisions under two emission reduction mechanisms

At a time, point K in the future, the government stipulates a target that the CO_2 emission intensity of the steel industry will decrease by R as compared to the base year CO_2 emission intensity. To achieve the target, each enterprise will make decisions about production and CO_2 emission intensity. The basic form of the profit function of each enterprise is as follows:

Table 1. Notations and explanations used in this paper

Notations	Explanations
Q	Steel production
P	The steel's price
α	The constant of the market inverse demand curve
β	The primary coefficient of the market inverse demand curve
q_i	Steel production of region i
$e_{2015,i}$	CO_2 emission intensity per ton steel of region i in 2015
e_i	CO_2 emission intensity per ton steel of region i at some stage
r_i	The decline range of CO_2 emission intensity per ton steel in region i
R	The decline target of national CO_2 emission intensity per ton steel
MAC	MAC curve in iron and steel industry
a_i	The quadratic coefficient of the steel industry's MAC in region i
b_i	The primary coefficient of the steel industry's MAC in region i
C_i	The cost function of the steel industry in region i
$C_{0,i}$	The production cost of the steel industry in region i
c_i	The cost of base period emission reduction in region i
e_0	Carbon emission benchmarks in carbon trading mechanism
T	The total carbon tax
t	The unit value of carbon tax
PP	Purchase price of carbon quota
SP	Selling price of carbon quota
CQ_i	Carbon quota of region i
W	Social welfare function
CS	Consumer surplus
PS	Producer surplus
$D(E)$	Total macro external environment loss of CO_2 emission
θ	The external loss parameter of CO_2
η	The production subsidies
m	The CO_2 emission reduced by the CCS demonstration project
A	The primary coefficient of the CCS demonstration project cost curve
B	The constant of the CCS demonstration project cost curve
π_i	The profit function of the steel industry in region i
E	The total CO_2 emissions in the iron and steel industry
S	The total subsidy
M	The total cost of the CCS demonstration project

$$\pi_{caseK,i} = P(Q)q_i - C_i q_i = (\alpha - \beta Q)q_i - q_i C_{0,i} - q_i \lambda\left(c_i + \int_0^{r_i} MAC_i(r)dr\right) - \mu_{Tax} te_i q_i + \mu_{S,Tax}\eta q_i + \mu_{Trade} CT_i + \mu_{S,Trade}\eta k_i q_i$$
$$= (\alpha - \beta Q)q_i - q_i C_{0,caseK,i} - q_i \lambda\left(c_i + \int_0^{r_i} MAC_i(r)dr\right) - \mu_{Tax} te_{2015,i}(1 - r_i)q_i + \mu_{S,Tax}\eta q_i + \mu_{Trade} CT_i + \mu_{S,Trade}\eta k_i q_i \quad (1)$$

In this formula, μ_{Tax}, μ_{Trade}, μ_S represent the probability of carbon tax policy, carbon trading policy and subsidy policy, respectively, $\mu_{S,\ Tax}$, $\mu_{S,\ Trade}$ correspond to the subsidy policy under the respective carbon emission reduction mechanism. In this paper, the values of all μs are either 1 or 0, which means the policy is implemented or not implemented, respectively.

$$CT_i = \begin{cases} SP \cdot \left[e_0 - e_{2015,i}(1 - r_i)\right] \cdot q_i, \ when\ e_0 \geq e_{2015,i}(1 - r_i) \\ PP \cdot \left[e_0 - e_{2015,i}(1 - r_i)\right] \cdot q_i, \ when\ e_0 < e_{2015,i}(1 - r_i) \end{cases} \quad (2)$$

$$k_i = \begin{cases} 0, \ when\ e_0 \geq e_{2015,i}\,(1 - r_i) \\ 1, \ when\ e_0 < e_{2015,i}\,(1 - r_i) \end{cases} \quad (3)$$

These two formulas represent that under a carbon trading policy, enterprises choose to buy or sell carbon quotas based on different carbon emissions benchmarks. The government subsidizes enterprises that purchase carbon quotas and does not subsidize enterprises that sell carbon quotas.

Let $\frac{\partial \pi_i}{\partial q_i} = 0$ and $\frac{\partial \pi_i}{\partial r_i} = 0$, and then the corresponding reduction range of emission intensity r_i and output q_i of iron and steel enterprises in each region can be obtained. The social welfare function has been expanded, and the specific form is as follows:

$$W_{CaseK} = CS + PS + \mu_{Tax} T - \mu_S S - D(E) - \mu_{CCS} M = \int_0^Q P(q)dq - P(Q)Q + \sum_{i=1}^{6}\pi_{caseK,i} + \mu_{Tax}\sum_{i=1}^{6} T_i - \mu_{S,Tax}\eta\sum_{i=1}^{6} q_i - \mu_{S,Trade}\eta\sum_{i=1}^{6} k_i q_i - \theta E - \mu_{CCS}(Am + B)$$
$$= \int_0^Q (\alpha - \beta q)dq - \left(\alpha - \beta\sum_{i=1}^{6} q_i\right)\sum_{i=1}^{6} q_i + \sum_{i=1}^{6}\pi_{caseK,i} + \mu_{Tax}\sum_{i=1}^{6} te_{2015,i}(1 - r_i)q_i - \mu_{S,Tax}\eta\sum_{i=1}^{6} q_i - \mu_{S,Trade}\eta\sum_{i=1}^{6} k_i q_i - \theta\sum_{i=1}^{6} e_{2015,i}(1 - r_i)q_i - \mu_{CCS}(Am + B) \quad (4)$$

where μ_{CCS} represents the CCS policy occurrence probability and the value is 0 or 1.

From the above formula, different value combinations of μ represent different combinations of emission reduction policies. Combined with the corresponding emission reduction target R, the government decision objective function (W) and basic constraints can be expressed as follows:

$$\max W$$
$$s.t. \begin{cases} \sum_{i=1}^{6} e_i q_i / \sum_{i=1}^{6} q_i = e_{2010}(1-R) \\ 0 < r_i < 1 \\ e_i < 0 \\ q_i < 0 \\ i = 1,2,3,4,5,6 \\ \ldots \end{cases} \tag{5}$$

3.3 Scenario assumptions

In the previous research (Duan *et al.*, 2019), three emission reduction scenarios in the near, medium- and long-term were set. This paper will follow these three emission reduction scenarios and examine the changes in the overall economic and environmental indicators of the steel industry under different emission reduction scenarios. The integrated emission reduction scenario of this paper is as follows:

- The steel industry will implement a single carbon emission reduction policy in 2020.

At present, China has no plan to implement and promote these two carbon emission reduction policies. Even if the steel industry implements carbon emission reduction policies soon, only a single emission reduction policy can be adopted due to policy and technical constraints as follows: that is, $\mu_S = 0$, $\mu_{CCS} = 0$. Then, the game model under this policy scenario is transformed into the following two scenarios: $\mu_{Tax} = 1$, $\mu_{Trade} = 0$ and $\mu_{Tax} = 0$, $\mu_{Trade} = 1$. When $\mu_{Tax} = 0$, $\mu_{Trade} = 1$, e_0 takes multiple values.

- Mixed emission reduction policy plan implemented in 2025: carbon tax + subsidy/ carbon trading + subsidy.

When the emission reduction target continues to increase, steel enterprises will face increasing pressure to reduce emissions and enterprises will invest more funds to reduce the intensity of the CO_2 emissions of their products, which will severely reduce the profit level of producers. The rebate subsidy based on product output can increase production enthusiasm and production capacity: that is, the mixed emission reduction scheme which $\mu_S = 1$ and $\mu_{CCS} = 0$. Then, the game model under this policy scenario is transformed into the following two scenarios: $\mu_{Tax} = 1$, $\mu_{Trade} = 0$, $\mu_{S,Tax} = 1$, $\mu_{S,Trade} = 0$ and $\mu_{Tax} = 0$, $\mu_{Trade} = 1$, $\mu_{S,Tax} = 0$, $\mu_{S,Trade} = 1$. When $\mu_{Tax} = 0$, $\mu_{Trade} = 1$, $\mu_{S,Tax} = 0$, $\mu_{S,Trade} = 1$, e_0 takes multiple values.

- Multiple mixed emission reduction schemes implemented in 2030: carbon tax + subsidy + CCS/carbon trading + subsidy + CCS.

When the emission reduction target is gradually raised, the implementation of subsidies may not fully achieve the CO_2 emission reduction target. CCS will play a large-scale CO_2 emission reduction role and will be put into operation in the medium- and long-term: that is, the multiple mixed emission reduction scheme which $\mu_S = 1$ and $\mu_{CCS} = 1$. Then, the game model under this policy scenario is transformed into the following two scenarios: $\mu_{Tax} = 1$, $\mu_{Trade} = 0$, $\mu_{S,Tax} = 1$, $\mu_{S,Trade} = 0$, $\mu_{CCS} = 1$ and $\mu_{Tax} = 0$, $\mu_{Trade} = 1$, $\mu_{S,Tax} = 1$, $\mu_{S,Trade} = 1$, $\mu_{CCS} = 1$. When $\mu_{Tax} = 0$, $\mu_{Trade} = 1$, $\mu_{S,Tax} = 0$, $\mu_{S,Trade} = 1$, $\mu_{CCS} = 1$, e_0 takes multiple values.

Section 4 analyzes these three emission reduction scenarios based on the constructed game model and calculates and compares the changes in the overall indicators in each emission reduction scenario. Then, the application scope of the CO_2 emission reduction policy is analyzed according to the results.

3.4 Data sources

The statistics in this paper are from the China Statistical Yearbook (NBS [National Bureau of Statistics of the People's Republic of China], 2021a), the China Industrial Statistical Yearbook (NBS [National Bureau of Statistics of the People's Republic of China], 2021b), the China Energy Statistical Yearbook (NBS [National Bureau of Statistics of the People's Republic of China], 2021c), the China Steel Yearbook (CISA [China Iron and Steel Association], 2021) and the statistical yearbooks of the various provinces. Relevant economic data are equivalent to comparable prices in 2010. The time span is from 2005 to 2016.

In addition, CO_2 emission data from industrial processes and product use (IPPU CO_2), which also produces a large amount of CO_2, is included in this paper. Therefore, CO_2 emissions accounting, emissions intensity and descent amplitude are based on energy consumption + IPPU CO_2 emissions.

Due to data availability, the steel industry's relevant energy consumption data and economic data are derived from the ferrous metal smelting and calendaring processing industry in the Statistical Yearbook. The CO_2 accounting data of fossil energy consumption and IPPU refer to IPCC (Intergovernmental Panel on Climate Change), (2006) and Duan *et al.* (2016).

4. Results and analysis

4.1 The results of parameter fitting

According to the research of Duan (2019) and the research ideas in this paper, this section analyzes the impact of these two emission reduction mechanisms (carbon tax and carbon trading) on the overall indicators of the steel industry at three time points, namely, 2020, 2025 and 2030. The inverse demand curve, emission reduction cost curve, CO_2 emission intensity reduction target, production cost, CCS curve, external macro environmental loss caused by CO_2 emissions and other functional relationships and parameters have referred to the previous research results (Färe *et al.*, 2007; Lee *et al.*, 2002; Guenno and Tiezzi, 1998).

In 2010, the average level of CO_2 emissions in China's steel industry was 3.1710 ton CO_2/ton steel 2 (the same below, omitted), the average level of CO_2 emission in 2015 was 2.8210. Correspondingly, the CO_2 emission levels of the six regions in 2015 were $e_1 = 2.3344$, $e_2 = 3.5698$, $e_3 = 2.9040$, $e_4 = 2.8779$, $e_5 = 3.2202$ and $e_6 = 4.5864$. The values and explanations of major parameters are shown in Table 2.

As for the selection of e_0 in the carbon trading mechanism, considering that China has just begun to implement a carbon trading mechanism, the initial carbon emissions benchmark value for the steel industry should not be set too high. After the system matures, the benchmark value setting should be stricter. Combined with related research, it is assumed that the benchmark value for 2020 is the average level of CO_2 emission intensity of the steel industry in 2015, which is 2.8210 ton CO_2/ton steel. In addition, the corresponding results are examined when the base value is 2.6953, 2.6636, 2.6319, 2.6002, 2.5685 and 2.5368 (a 15%–20% reduction compared with the national level in 2010).

It is assumed that the benchmark value in 2025 is 2.3782 (25% lower than the national emission level in 2010), and the corresponding results are examined when the base value is 2.3465, 2.3148, 2.2831, 2.2514 and 2.2197 (26%–30% lower than the national emission level in 2010).

It is assumed that the benchmark value in 2030 is 2.2197 (30% lower than the national emission level in 2010) and the corresponding results are examined when the base value is 2.1880, 2.1563, 2.1246, 2.0929 and 2.0611 (31%–35% lower than the national emission level in 2010).

In the selection of examination indicators, this paper selects four indicators – total output, overall social welfare, producer surplus and macro-environment losses caused by CO_2 for measuring these two policies3 (carbon tax and carbon trading). These operating data are also more concerned by the steel industry and government departments.

4.2 Empirical analysis

4.2.1 Single carbon emission reduction scheme in 2020. In this scenario, this paper will analyze and compare the changes in the total output, social welfare, producer surplus and macroeconomic environmental losses under a single carbon tax and under a single carbon trading policy. The emission reduction scenario proposes that the CO_2 emission intensity of the steel industry in 2020 will be reduced by 15% as compared to the CO_2 emission intensity in 2010 and the changes of various indicators will be also considered when the reduction target is 15%–20%.

With a reduction target of 15%–20%, under a single carbon tax mechanism, the total output is maintained at about 846–851 million tons, the social welfare is maintained at an economic level of about 5.90×10^{12}–5.91×10^{12} Yuan, the producer surplus is sustained at an economic level of about 1.81×10^{12}–1.82×10^{12} Yuan and the macro-environmental losses caused by CO_2 emissions remain at around 3.12×10^{10}–3.34×10^{10} Yuan. Under a single carbon trading mechanism, total output is maintained at about 854–855 million tons, the social welfare is maintained at about 5.91×10^{12}–5.93×10^{12} Yuan and the producer surplus is maintained at about 1.82×10^{12}–1.83×10^{12} Yuan. The macro environmental loss remains at around 3.15×10^{10}–3.35×10^{10} Yuan.

The comparison of the total output under the single carbon tax policy versus the single carbon trading policy is shown in Figure 1. With the gradual increase of emission reduction targets, a carbon tax mechanism will reduce the product output while the carbon trading mechanism has the opposite effect. Although the carbon emission benchmark value has changed, the product output does not change relative to emission reduction targets. With the

Notations	Unit		$i = 1$	$i = 2$	$i = 3$	$i = 4$	$i = 5$	$i = 6$
$e_{2015,i}$	$t\ CO_2/t$		2.3344	3.5698	2.9040	2.8779	3.2202	4.5864
a_i	–		11,661	17,208	16,932	12,952	6,397.2	3,485
b_i	–		−169.76	8,876.7	−166.92	1,483.6	502.52	421.13
c_i	Yuan		2,168.2	3,511.1	2,165.4	3,325.1	2,368.7	3,814.3
$C_{0,2015,i}$	Yuan	2015	2,833.15	4,898.47	3,453.53	4,153.15	3,799.03	3,832.38
		2020	2,124.86	3,918.77	2,590.15	2,491.89	3,609.08	3,640.76
		2025	1,699.89	2,743.14	2,072.12	1,868.92	3,067.72	3,094.64
		2030	1,444.91	2,194.51	1,761.30	1,588.58	2,454.17	2,475.71

Table 2.
Some parameter values

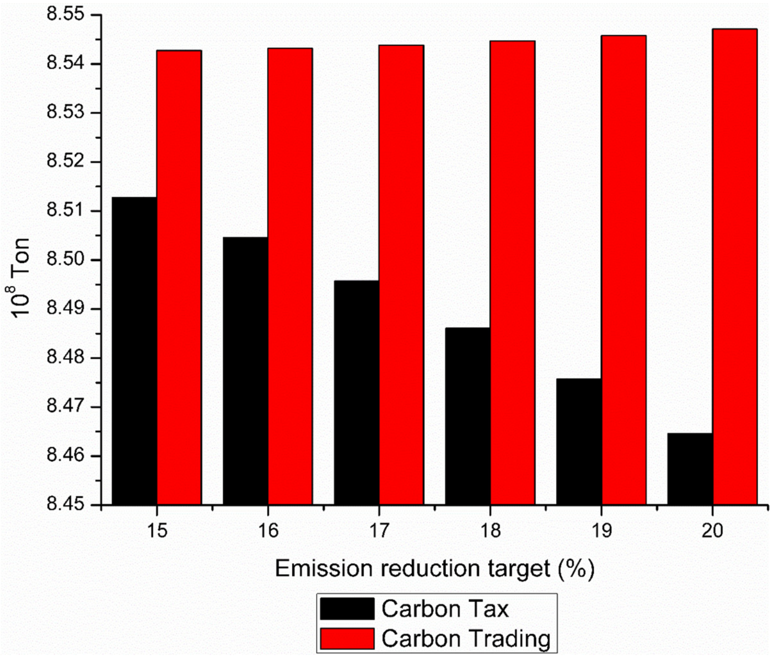

Figure 1. Comparison of total output under single carbon tax and single carbon trading policy

gradual increase in emission reduction targets, the output difference between the two policies gradually widens.

As shown in Figure 2, with the gradual increase in emission reduction targets, a carbon tax mechanism will reduce social welfare while the carbon trading mechanism has the opposite effect. When the emission reduction targets remain unchanged, social welfare under the carbon trading mechanism will gradually decline with the decrease in the carbon emission benchmarks. After calculation, when the emission reduction target is 15% and $e_0 = 2.2514$, the social welfare level under the carbon trading mechanism is the same as the social welfare level under the carbon tax mechanism. In this case, e_0 is equivalent to 80% of the initial value of 2.8210. In the initial stage of implementing the carbon trading mechanism, in terms of carbon quota allocation according to the benchmark method, this value is relatively low. In addition to the CO_2 emission intensity in North China, there is still a certain gap in other regions, which will have difficulty achieving this emission intensity. This shows that the carbon trading mechanism with a higher base value is more successful than the carbon tax mechanism in terms of social welfare.

As shown in Figure 3, with the gradual increase of emission reduction targets, a carbon tax mechanism will reduce the producer surplus while the carbon trading mechanism has the opposite effect. When the emission reduction targets remain unchanged, producer surplus under the carbon trading mechanism will gradually decline with the decrease in the benchmarks. After calculation, when the emission reduction target is 15% and $e_0 = 2.2514$, the producer surplus level under the carbon trading mechanism is the same as the producer surplus level under the carbon tax mechanism. In this case, e_0 is equivalent to 80% of the initial value level of 2.8210. Similar to social welfare, the carbon trading mechanism with a

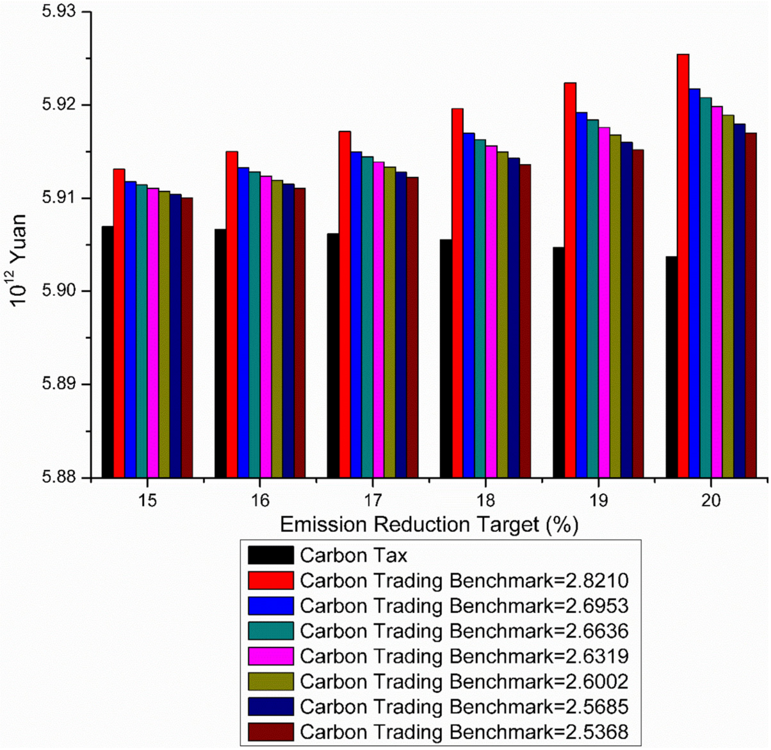

Figure 2.
Comparison of overall social welfare under a single carbon tax and single carbon trading policy

higher base value is more successful than the carbon tax mechanism in terms of producer surplus.

As shown in Figure 4, under the carbon trading mechanism, the macro-environmental losses caused by CO_2 emissions do not change and are related only to the emission reduction targets. With the gradual increase in emission reduction targets, the carbon tax mechanism and the carbon trading mechanism will both reduce the macro environmental loss. However, the macro losses under the carbon tax mechanism are lower than those under the carbon trading mechanism and as the emission reduction target gradually increases, the difference gradually increases.

4.2.2 Mixed emission reduction schemes in 2025. According to calculations, with a reduction target of 20%–25%, under the carbon tax + subsidy mechanism, the total output, social welfare and emissions losses show a downward trend while the producer surplus rises because of the subsidy policy. The total output is maintained at about 900 million tons, the social welfare is maintained at about 6.42×10^{12}–6.43×10^{12} Yuan and the producer surplus is maintained at about 1.87×10^{12}–1.88×10^{12} Yuan. The macro-environmental loss remains at 3.11×10^{10}–3.33×10^{10} Yuan, and the total subsidy gradually increases from 1.07×10^{11} Yuan to 1.80×10^{11} Yuan. Under the carbon trading + subsidy mechanism, the total output is maintained at about 900 million tons, social welfare is maintained at about 6.41×10^{12}–6.42×10^{12} Yuan and the producer surplus is maintained at about 1.87×10^{12}–1.88×10^{12} Yuan. The macro environmental loss is maintained at 3.12×10^{10}–3.33×10^{10}

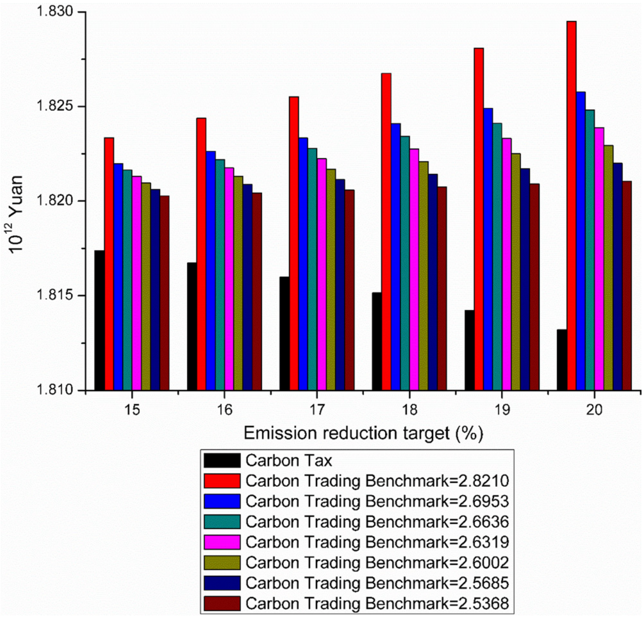

Figure 3. Comparison of producer surplus under single carbon tax and single carbon trading policy

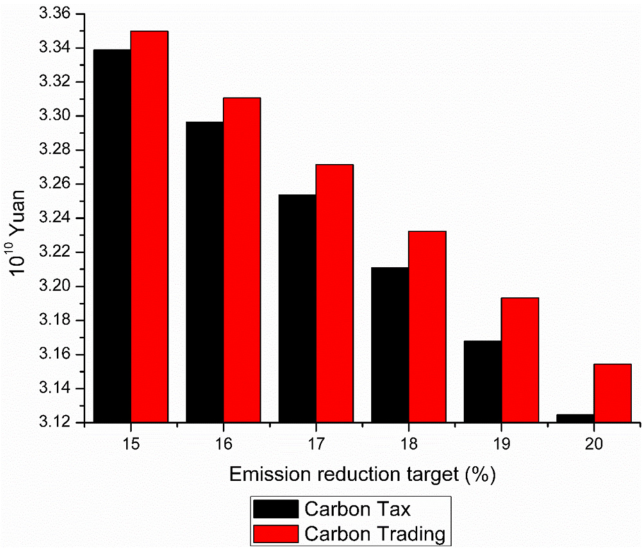

Figure 4. Comparison of macro environmental losses under single carbon tax and single carbon trading policy

Yuan, and the total subsidy is controlled in the range of 1.01×10^{10} Yuan to 1.89×10^{10} Yuan.

As shown in Figure 5, this 2025 scenario is different from the 2020 emission reduction scenario. Both mechanisms will reduce the output, but the output decline is even more pronounced under the carbon tax mechanism; with the gradual increase of emission

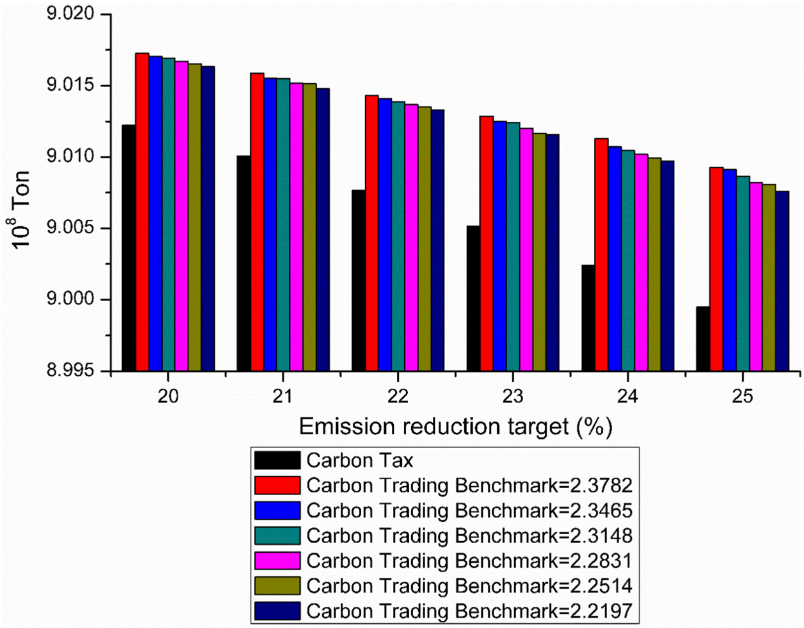

Figure 5.
Comparison of total output under carbon tax + subsidy and carbon trading + subsidy policy

reduction targets, the output under the carbon trading mechanism will decrease as the benchmark changes less dramatically. The output under the carbon trading mechanism is higher than that under the carbon tax mechanism in the same emission reduction target comparison.

As shown in Figure 6, with the gradual increase of emission reduction targets, the carbon tax + subsidy emission reduction mechanism will reduce the social welfare while the carbon trading + subsidy mechanism results are more complicated. When the benchmark value is higher (greater than 2.2514), social welfare will increase with the increasing emission reduction target; however, when the benchmark value is lower (less than 2.2514), social welfare will decrease with the increasing emission reduction target. Except for a few data points (i.e. the emission reduction target is 25% and the carbon emission benchmark value is 2.3782), the social welfare under the carbon tax mechanism is higher than that under the carbon trading mechanism in the same emission reduction target comparison. This shows that in the comparison of the social welfare factor, with the gradual rigorous setting of emission reduction targets and emission benchmarks, in most cases, the carbon tax mechanism is more successful in improving the various outcome factors than the carbon trading mechanism under the same conditions.

As shown in Figure 7, both mechanisms will increase the producer surplus. Except for a few data points (i.e. the emission reduction target is 25%, and the carbon emission benchmark value is 2.3782), under the same emission reduction target, the producer surplus under the carbon tax mechanism is higher than that under the carbon trading mechanism. This shows that in the comparison of the producer surplus outcome factor, with the gradual setting of more and more strict emission reduction targets and emission benchmarks, in most cases, the carbon tax mechanism is more effective than the carbon trading mechanism under the same conditions.

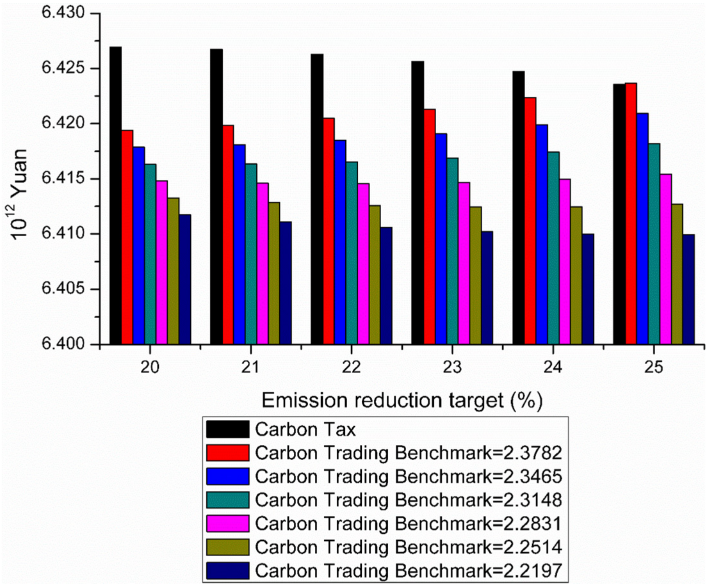

Figure 6. Comparison of overall social welfare under carbon tax + subsidy and carbon trading + subsidy policy

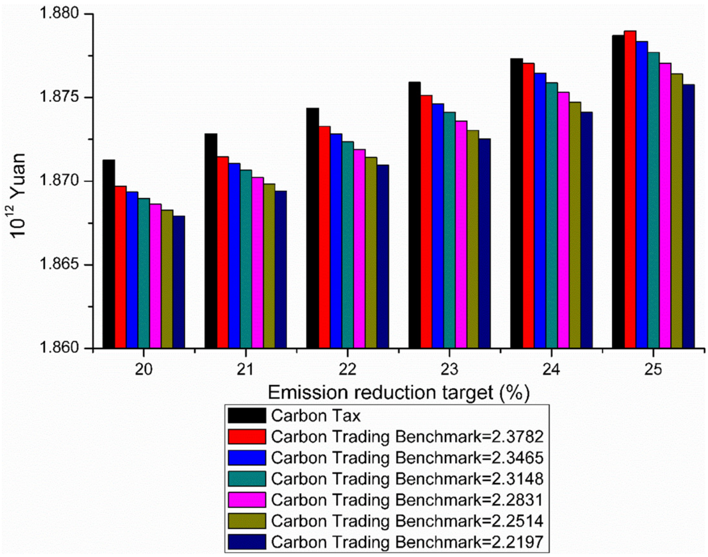

Figure 7. Comparison of producer surplus under carbon tax + subsidy and carbon trading + subsidy policy

As shown in Figure 8, the overall difference between the two mechanisms (carbon tax and carbon trading) is not large and the loss value under the carbon trading mechanism is slightly higher than that under the carbon tax mechanism. With the gradual increase of emission reduction targets, the loss values decrease under both of the mechanisms. Under the same emission reduction target, the loss changes under the carbon trading mechanism

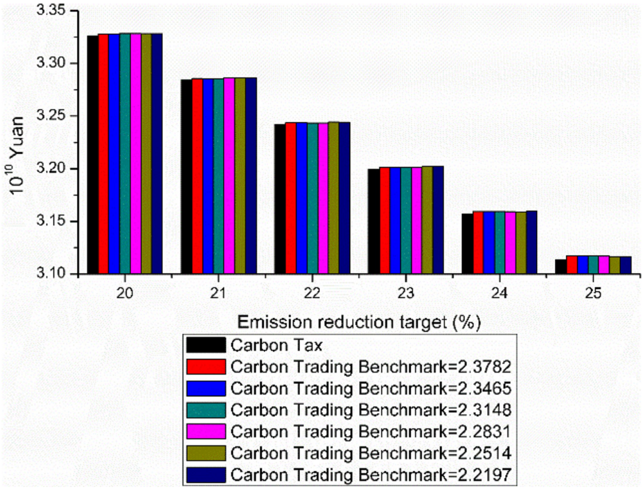

Figure 8.
Comparison of macro environmental losses under carbon tax + subsidies and carbon trading + subsidy policies

are more complex; namely, the values are relatively similar and there is no clear rule governing any changes. This is due to the combined effect of subsidy policies and different benchmark values, such that CO_2 emissions do not show a clear linear trend.

As shown in Figure 9, it is clear that under the carbon trading mechanism, different enterprises will choose to sell or buy carbon quotas according to their own emission intensity. This aspect of the transaction largely offsets the subsidies for products. Therefore, the total subsidy under the carbon tax mechanism is much larger than the result under the carbon trading mechanism. Under the same emission reduction target, the total subsidy changes under the carbon trading mechanism are more complex; again, the values are relatively similar and there is no rule or equation that governs the changes. This is due to the

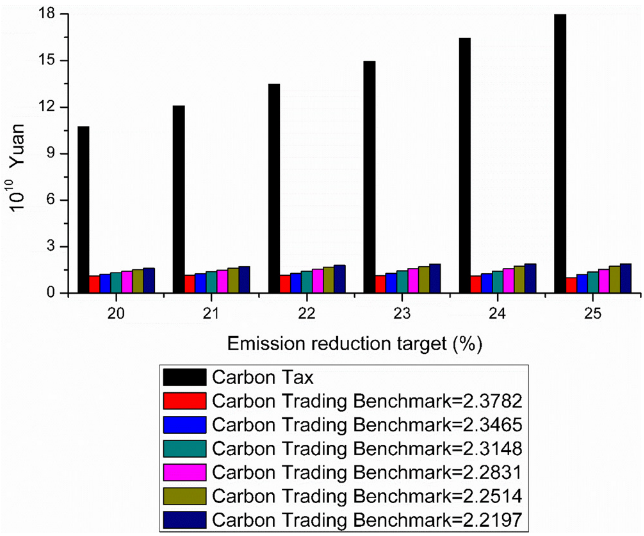

Figure 9.
Comparison of total subsidies under carbon tax + subsidies and carbon trading + subsidy policies

combined effect of subsidy policies and different benchmark values, such that the total subsidy does not show a clear linear trend.

4.2.3 Multiple mixed emission reduction schemes in 2030. According to calculations, with a reduction target of 25%–30%, under the carbon tax + subsidy + CCS mechanism, the total output, social welfare and emissions losses show a downward trend while the producer surplus rises because of the subsidy policy. The total output is maintained at about 931–933 million tons, the social welfare is maintained at about 6.76×10^{12}–6.77×10^{12} Yuan, the producer surplus is maintained at about 1.88×10^{12} Yuan, the macro environmental loss is maintained at about 3.01×10^{10}–3.23×10^{10} Yuan, and the total subsidy gradually increases from 2.02×10^{11} Yuan to 2.82×10^{11} Yuan. Under the mechanism of carbon trading + subsidies + CCS, the total output is maintained at about 932–934 million tons, social welfare is maintained at about 6.73×10^{12}–6.76×10^{12} Yuan and the producer surplus is maintained at about 1.88×10^{12}–1.89×10^{12} Yuan. The macro-environmental losses remain around 3.01×10^{10}–3.23×10^{10} Yuan and the total subsidy is controlled in the range of 1.76×10^{10} Yuan to 3.13×10^{10} Yuan.

As shown in Figure 10, with the gradual increase of emission reduction targets, these two mechanisms will both reduce the output, but the output decline under the carbon tax mechanism is more obvious. The output under the carbon trading mechanism is higher than that of carbon tax mechanism products under the same emission reduction target. However, the production under the carbon trading mechanism changes in complex ways as follows: when the emission reduction target is low (25%–28%), the lower the carbon emission benchmark, the lower the total output; when the emission reduction target is high (29%–30%), the total output fluctuates significantly.

As shown in Figure 11, with the gradual increase in emission reduction targets, the carbon tax + subsidy + CCS mechanism will reduce the social welfare while the carbon trading + subsidy mechanism results are more complicated. When the benchmark is higher (greater than 2.1880), social welfare will increase as the emission reduction target increases; when the benchmark is lower (less than 2.0930), social welfare will decrease as the emission reduction target gradually increases; when the benchmark falls in between these values,

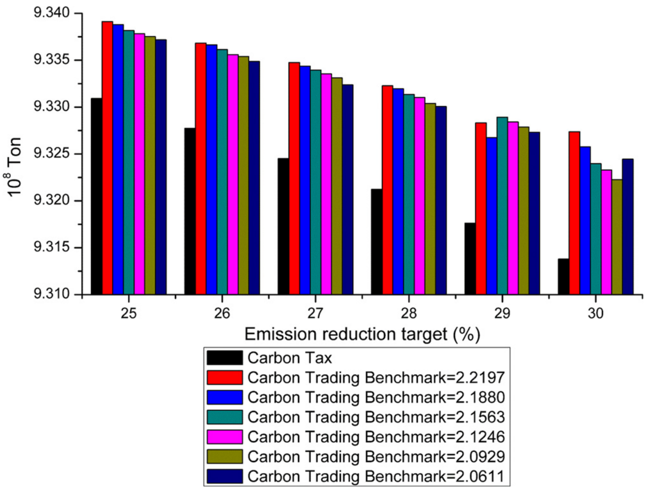

Figure 10.
Comparison of total output under carbon tax + subsidy + CCS and carbon trading + subsidy + CCS policy

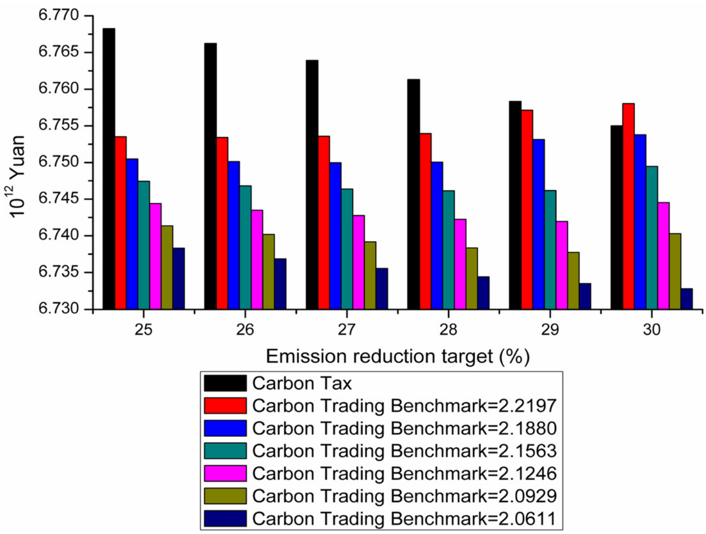

Figure 11.
Comparison of overall social welfare under carbon tax + subsidy + CCS and carbon trading + subsidy + CCS policy

there is no obvious rule that governs the results for social welfare. Except for a few cases (i.e. the emission reduction target is 30% and the carbon emission benchmark is 2.2197), the social welfare under the carbon tax mechanism is higher than that under the carbon trading mechanism under the same emission reduction target. This shows that in the comparison of social welfare, with the gradual rigorous setting of emission reduction targets and emission reduction benchmarks, in most cases, the carbon tax mechanism is more effective for improving outcome factors than the carbon trading mechanism under the same conditions.

As shown in Figure 12, both mechanisms will increase the producer surplus outcome. When the emission reduction target is low (25%–28%), under the same emission reduction target, the producer surplus under the carbon tax mechanism is higher than that under the carbon trading mechanism; when the emission reduction target is high (30%), under the same emission reduction target, the producer surplus under the carbon trading mechanism is higher than that under the carbon tax mechanism (except for the benchmark value of 2.0611); when the emission reduction goal falls between these values, the higher the benchmark, the higher the producer surplus under the carbon trading mechanism. This shows that with the gradual rigorous setting of emission reduction targets and emission reduction benchmarks, attention must be focused on the relative changes of these two indicators (emission reduction targets and emission reduction benchmarks) at the same time to make an appropriate choice.

It can be seen from Figure 13 that the loss value under the carbon trading mechanism is slightly higher than that under the carbon tax mechanism. With the gradual increase of emission reduction targets, the loss values under both mechanisms decrease. Also, the total subsidy has a similar conclusion in Section 4.2.2.

5. Discussion

Regarding the choice of these two emission reduction policies, different from other economic scholars' research perspectives, this paper does not focus on the perspective of operating costs, policy feasibility, etc., but rather take the results as a guide to analyze the impact of

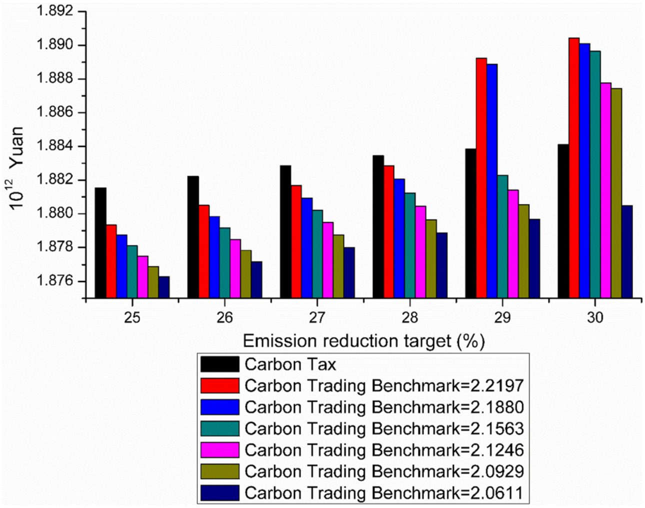

Figure 12. Comparison of producer surplus under carbon tax + subsidy + CCS and carbon trading + subsidy + CCS policy

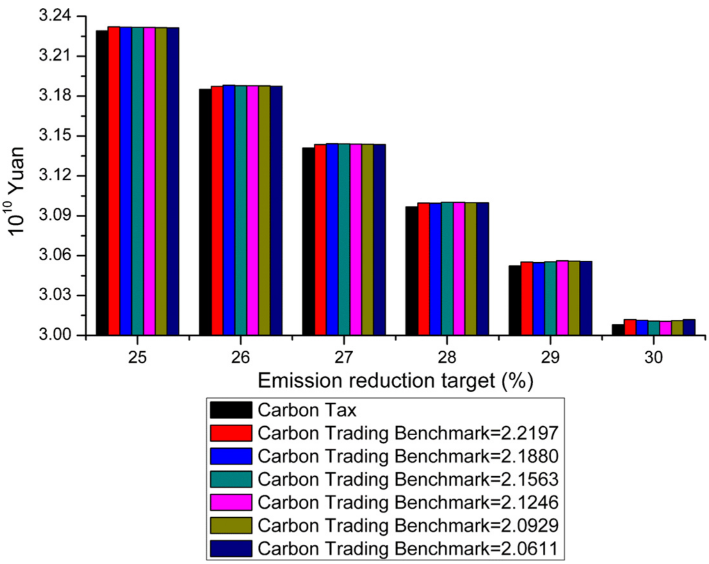

Figure 13. Comparison of macro environmental losses under carbon tax + subsidy + CCS and carbon trading + subsidy + CCS policy

the implementation of the two emission reduction policies on the overall indicators of the steel industry.

As for the carbon tax policy, the essence is to internalize external costs through taxation, so as to influence the decision-making behavior of economic entities and achieve the goal of reducing emissions. Therefore, for an energy-intensive industry such as the steel industry, the imposition of a carbon tax will have an impact on industry output and competitiveness at least in the short-term. It can be seen from the results that in most emission reduction scenarios, the total output under the carbon tax policy is lower than the corresponding result under the carbon trading policy. Even in some emission reduction scenarios (especially in the comparison of single carbon emission reduction policies), economic indicators such as producer surplus and social welfare are lower than the corresponding results under the carbon trading policy. However, from a medium- and long-term perspective, the carbon tax mechanism still has certain advantages in terms of producer surplus and social welfare. In terms of macro environmental losses, the results under the carbon tax policy are slightly lower than the results under the carbon trading mechanism, but there is not much difference between the two.

For carbon trading policies, as the transfer of emission quotas is completed through market transactions, low-emission producing companies can form surplus emission quotas through emission reduction activities and sell them to obtain certain benefits; high-emission producing companies need to pay a certain fee. Therefore, the economic exchanges and game behaviors between enterprises are more complicated than they are under the carbon tax mechanism. In addition, considering multiple carbon emission benchmarks and multiple emission reduction policy combinations, the changes in results are more complex. In the near term (comparison of single carbon emission reduction policies), carbon trading policies have certain advantages in terms of total output, producer surplus and social welfare. In the medium-term and long-term, due to the combined effects of subsidy policies and carbon emissions benchmarks, carbon trading policies are superior to carbon taxation in terms of total output and total subsidies.

Through calculation, we can also find that in individual cases, the carbon trading mechanism is slightly more effective than the carbon tax mechanism in terms of overall social welfare and producer surplus. This shows that even under the same emission reduction target, due to the combined effect of multiple factors, the choice between the two emission reduction policies is not absolute, but rather needs to be considered in the context of a comprehensive consideration of emission reduction targets and emission reduction policies. This shows that the discussion of the two policies needs to be based on objective and comprehensive facts. In addition, this is also the focus and the practical significance of this paper.

6. Conclusions

This paper considers a variety of emission reduction policies and different carbon emission benchmark values and it constructs a production decision game model for the steel industry under a carbon tax mechanism and a carbon trading mechanism. The main conclusions are as follows:

Both a single carbon tax mechanism and a single carbon trading mechanism will reduce the macro-environmental loss, but the implementation of the carbon tax mechanism will cause less loss. With the gradually increasing reduction target, the gap between the two policies will gradually widen. Moreover, the macro losses are related only to the emission reduction targets. With the gradual increase of emission reduction targets, a carbon tax mechanism will reduce the social welfare and producer surplus while a carbon trading mechanism will have the opposite effect. When the emission reduction target remains unchanged, the social welfare and producer surplus under the carbon trading mechanism will gradually decline as the carbon emission benchmark decreases. A carbon trading mechanism with a higher carbon emission benchmark is more effective than a single carbon tax mechanism.

When considering various emission reduction policies, in most cases, the mixed carbon trading mechanism is more effective than the mixed carbon tax mechanism in terms of total output and total subsidies. Meanwhile, the mixed carbon tax mechanism is superior to the mixed carbon trading mechanism in terms of overall social welfare, producer surplus and macro losses. However, this conclusion is not absolute. Rather, the choice between the two emission reduction mechanisms needs to be comprehensively considered according to the relative relationship between the emission reduction targets and the carbon emission benchmark.

Based on the conclusions and related analysis, this paper suggests that the steel industry should consider certain factors when selecting and combining emission reduction policies; these factors are explained below.

At the beginning of the implementation of either of the two emission reduction policies or a single carbon trading policy is shown to be superior to a single carbon tax policy for achieving certain outcomes. With the gradual improvement and promotion of emission reduction policies, supplemented by other supporting policies such as subsidies, the choice between the two mechanisms needs to be carefully selected according to the emission reduction targets and the requirements for economic indicators. In most cases, if the steel industry focuses more on product output, it is more appropriate to implement a carbon trading policy; if the steel industry focuses more on overall economic indicators, it is more reasonable to implement a carbon tax policy. Therefore, when choosing among more detailed emission reduction policies, more complex emission reduction situations and more stringent emission reduction requirements, to make a reasonable choice, steel industry decision-makers need to carefully consider the combined effects of multiple factors.

Notes

1. According to the characteristics of statistical data, this paper merges the seven geographical regions of China into six regions, for which the South Central China region includes Central China and South China.
2. In this paper, all data are macro from the statistical yearbook and other statistical material. At present, China still lacks the production and consumption data of all enterprises in each region. Therefore, the emission intensity, output and other data in this paper are based on the macro statistical data or the average value for each region.
3. In fact, the corresponding results for each region are also calculated. Because the regions' change trends results are the same as the overall results, so the analysis results for each region are not reported in this paper.

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