Research on the influence of product differentiation and emission reduction policy on CO_2 emissions of China's iron and steel industry

Ye Duan

School of Geography, Liaoning Normal University, Dalian, China

Zenglin Han

Center for Studies of Marine Economy and Sustainable Development, Liaoning Normal University, Dalian, China, and

Hailin Mu

Key Laboratory of Ocean Energy Utilization and Energy Conservation of Ministry of Education, Dalian University of Technology, Dalian, China

Abstract

Purpose – There are certain differences in the production products of enterprises. What are the impacts of product differentiation on the iron and steel industry? Based on the macro background of CO_2 emission reduction, this paper aims to analyze the economic benefits and environmental changes of the iron and steel industry under the dual influence of CO_2 emission reduction policy and product differentiation policy.

Design/methodology/approach – Taking the basic data of iron and steel industry in six regions of China as an example, this paper constructed an extended two-stage dynamic game model to analyze the impact of product differentiation and carbon tax policy on the production, economic indicators and CO_2 emission levels for the overall industry and regional enterprises.

Findings – As the CO_2 emission reduction target increased, the unit carbon tax and total tax increased, whereas the macro-environmental losses, social welfare, consumer surplus and outputs decrease. Emission reduction pressures and other economic indicators showed obvious regional differences. Differentiated

products promoted various indicators of enterprises and industries; higher degrees of product differentiation resulted in greater promoting effects on economic indicators.

Originality/value – This paper constructed multiple emission reduction and production backgrounds, and discusses the impact of the comprehensive implementation of these policies, which has been practically absent in previous studies. The results of this study are consistent 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.

1. Introduction

The iron and steel industry (hereinafter referred to as the "steel industry") is an indispensable sector for China's economic development. The iron and steel industry has provided important raw materials to support national construction, has promoted industrialization and modernization in the national industry, and has improved people's livelihoods.

The "Steel Industry Adjustment and Upgrading Plan (2016–2020)" noted that China's crude steel output reached a historical peak of 820 million tons in 2014 as a consequence of rising demand. The domestic market share exceeds 99%, which essentially meets the demand for steel in national economic and social development. Moreover, 90.89 million tons of ironmaking capacity and 94.86 million tons of steelmaking capacity were eliminated. The comprehensive energy consumption per ton of steel (equivalent to standard coal) of key large and medium-sized enterprises decreased from 605 kg to 572 kg and the sulfur dioxide emission per ton of steel decreased from 1.63 kg to 0.85 kg. The emission of fume and dust per ton of steel decreased from 1.19 kg to 0.81 kg, and the new water consumption per ton of steel decreased from 4.10 tons to 3.25 tons, reaching the "Twelfth Five-Year Plan" target. The total energy consumption of steel is declining.

Although China has become the world's largest steel producer, the steel industry also faces many problems:

In terms of economic operation, the debt ratio of key large and medium-sized enterprises in China's iron and steel industry exceeded 70%. The utilization rate of crude steel production capacity dropped from 79% in 2010 to approximately 70% in 2015. Steel production capacity has gradually evolved from a regional and structural surplus to an absolute surplus. The entire industry has been operating at low profits for a long time.

In the production of steel products, the level of independent innovation is not high. Enterprise R&D investment accounts for only approximately 1% of main business income, which has not reached the target of "1.5% or more" in the "Twelfth Five-Year Plan," which is far below the level of more than 2.5% in developed countries. The problems of product homogeneity and low quality still exist. With the expansion of new capacity of the same type of steel, a large number of repeated allocations of innovative resources, such as capital, equipment and talents, have led to the increased homogeneity of products. The ability of innovation to lead development is not pronounced; the product quality is low; and the old model of imitation, digestion and absorption is still used. Some key high-end steel varieties still need to be imported.

Furthermore, many steel enterprises have not yet achieved full and stable pollutant emissions, and energy-saving and environmental protection facilities need to be further upgraded. Although energy consumption and pollutant emissions per ton of steel have been

declining annually, they cannot offset the increase in total energy consumption and total pollutants caused by the increase in steel production. It is precisely that environmental problems in the steel industry have not been improved for a long time because of the increase in steel production.

In the future, the market not only needs threaded steel, wire, small profiles and other ordinary steel but also high-end steel components. The failure to make adjustments will seriously affect the survival and development of enterprises. In a changing market scenario, adopting product differentiation strategies will enable enterprises and industries to better adapt to future changes, and relevant research will gradually become important domestic concerns and issues.

Emission reduction policies, such as carbon trading and carbon taxes, have not been fully implemented and their impacts on the production level and profit of enterprises and the steel industry remain unclear. Emission reduction targets need to be more stringent to ensure that energy conservation is achieved. Future development measures should begin from the consideration of energy conservation and pollutant emission reduction, product structure and corporate decision-making. This paper focuses on the impact of product differentiation and emission reduction policies on the production and CO_2 emission reduction of the steel industry.

2. Literature review

Product differentiation models are widely used in industrial economics and other disciplines. The basic theoretical models included the Bowley (1924) model, Shubik and Levitan (1980) model and Hotelling (1929) model. Product differentiation theory is usually studied together with other theoretical combinations to make comparisons of homogeneous products.

Shaked and Sutton (1982) established a three-stage oligarchy game model and suggested that high-quality products can drive price declines. Chang (1991) found that higher product differentiation resulted in a greater tendency for pricing to be collusive between manufacturers. Goldberg (1995) studied product differentiation and oligopolies in the international market through empirical analysis of USA companies. Meng *et al.* (2018) examined the product selection strategies for two horizontally competitive firms under different power structures while considering the effect of a carbon tax rate. Li and Chen (2018) developed a game model to study a supply chain in which two manufacturers supply a product in quality-differentiated brands to a common retailer. Yakita and Yamauchi (2011) studied the environmental R&D strategy of enterprises in the duopoly model with horizontal differentiation and found that when the degree of product differentiation is large, the spillover of environmental R&D cooperation technology reduces the total social emission level. Gautier (2014) studied the role of product differentiation in the environmental policy reforms of two countries and found that reductions in foreign subsidies reduce country profits, production and pollution emissions as product differentiation increases. Kugler and Verhoogen (2012) found that there is a positive relationship between the scale of the enterprise and the output price in heterogeneous industries, but this relationship does not exist in homogeneous industries.

In the industry sector, the application of product differentiation theory is extensive. For example, Li *et al.* (2005) studied the competitiveness level under the conditions of product differentiation in the textile and garment industry. Yang (2009) introduced the ideas of supply chain coordination and value-added service variables into the tourism industry. Fu *et al.* (2011) established a price response model that closely reflects the ideal demand system and operator and studied the degree of substitution of service offerings between different airlines. Gebauer *et al.* (2011) pointed out that by providing differentiated services, manufacturing companies can gain a

competitive advantage. Altug (2016) identified two main economic distortions with a vertically differentiated two-product model in the semi-conductor industry and analyzed several other supply chain contracts for manufacturers selling vertically differentiated products both in monopolistic and competitive settings. In the steel industry, Ma (2005) identified causes of differentiation through a multi-factor analysis of product differentiation, combined with the characteristics of Wuhan Iron and Steel Company silicon steel products, to determine a competitive strategy and propose an implementation plan. Feng (2012) proposed suggestions for the development of high-quality steel and diversified development models for new trends in the steel industry. Gao and Lou (2012) pointed out that the development strategies of many domestic steel companies include scale expansion strategies. Blindly expanding the scale without a foundation for technological innovation does not facilitate the growth of domestic steel companies but leads to greater overcapacity. Li (2015) believed that Chinese steel companies should develop high-end products, accelerate the construction of independent R&D systems and combine major engineering and equipment construction breakthroughs in addition to eliminating backward products and upgrading large-scale products. Qiao *et al.* (2018) suggested that adjusting the industrial structure and product structure, developing and introducing advanced production technologies and developing high-end steel products are important for promoting the sustainable development of the steel industry. Wang (2017) suggested that the product structure of iron and steel enterprises is diverse and that appropriate adjustments should be made to accommodate historical progress and the advancement of social processes. Technological upgrades and structural adjustment are closely related to the management of the product structure of the enterprise. Yu (2018) suggested that China's steel industry has now entered a new stage of high-quality development. To achieve product structure adjustment, the most important aspect requiring consideration is the research and development of new steel products. Research and development also enhance the core competitiveness of steel companies and can facilitate sustainable development.

CO$_2$ emission reduction policy relates to technological changes and alternate ways of reducing resource inputs and unit output emissions. In light of the current state of the industrial sector in China, environmentalists and policymakers are often more inclined to use economic incentive-based emission reduction policies. Mann (2009) suggested that a carbon tax should be used for its ease of implementation, the favorable emission reduction path for enterprises, and the small scope for local governments to implement local protectionism. Goto (1995) used the computable general equilibrium (CGE) model to study the economic impact of carbon tax levies. Govinda and Ram (2002) used the CGE model to analyze tax returns in Thailand by using the tax return method of returning to the family or reducing the income tax. Wissema and Dellink (2007) used a CGE model to simulate the impact of the carbon tax on the Irish economy and environment. Tim *et al.* (2009) studied the impact of a carbon tax on the income of Irish nationals. Guo *et al.* (2012) established a CGE model of a fossil energy sector with seven modules to analyze the corresponding impact of carbon tax policies in a low-carbon economy. Grant *et al.* (2014) explored the economic and environmental impacts in Scotland of three cases (carbon tax non-return, carbon tax for public base expenditures and income tax revenue reduction) by building a CGE model.

Helen *et al.* (2015) used the CGE model to simulate the impact of the carbon tax on energy efficiency and structure in the Philippines. Zhu (2015) and Qian (2016) used the CGE model to analyze the impact of a carbon tax on the social and economic aspects of Zhejiang Province under the returning policy or implementing a carbon tax substitution policy. Benavente (2016) used the CGE model to simulate the carbon tax rate required to achieve Chile's goal of reducing CO$_2$ emissions by 20%, followed by an assessment of its impact on the economy. Wu *et al.* (2016) and Wang *et al.* (2017) used the CGE model to study the effects of carbon taxation on social and

economic reductions in Henan and Jiangsu, China in terms of returning residents and businesses. Yahoo and Othman (2017) used the CGE model to analyze Malaysia's economy and emissions reductions based on carbon tax levy and carbon trading. Li and Su (2017) used a CGE model to study the carbon recovery schemes of different carbon tax collection departments in Singapore. Chen *et al.* (2017) established an energy CGE model of Guangdong Province and simulated the energy-saving and emission reduction effects of an energy tax or carbon tax, followed by an analysis of the mitigation effects on the economic system based on tax refund plans. Ling *et al.* (2017) developed a multi-sectoral dynamic CGE model using a coal resource tax module and studied the overall impacts of the coal resource tax reform policy on the Chinese economy and environment. In such models, there was a clear deviation between the results and the actual data. Moreover, the requirements of the social accounting matrix are high and are not published every year.

Several studies have taken a game-theoretical perspective to explore environmental regulations and carbon tax mechanisms. Such studies often focus on a two-stage game model to establish the relationship between government and enterprises or among different enterprises. The optimal emissions level and the optimal output subsidy mechanism have received the most attention.

Poyago-Theotoky (2007) showed that when the government imposes a carbon tax, enterprises experience spillover effects because of research and development of emission reduction. Gregmar and Jonathan (2010) studied carbon tax collection and subsidies in the USA based on the utility maximization model. Yu and Zhang (2013) established a three-stage game model between government and enterprises and analyzed the feasibility and mode selection of the carbon tax policy. Krass *et al.* (2013) analyzed the impact of a carbon tax on corporate emission reduction technology through the Stackelberg game model. Through an empirical study of a clothing supply chain, Choi (2013) found that the implementation of a carbon tax policy can effectively promote sustainable supply chain management. Shi *et al.* (2013) explored the optimal abatement cost decision and corporate social and economic benefits in the context of the government's carbon tax policies. Ouchida and Goto (2014) concluded that social welfare under a time-consistent emission tax (emission subsidy) policy enhances welfare more than *laissez-faire* approaches. Qiao *et al.* (2014) used the non-cooperation game theory to study the carbon tax strategies of EU airlines. Xu *et al.* (2016) studied production decision-making of manufacturer's and pricing decisions under a carbon tax policy and compared the total carbon emissions, maximum profits and social welfare of firms under a carbon cap and carbon trading policies. Cao *et al.* (2017) used the Stackelberg game to study the optimal production and carbon emission reduction levels under cap-and-trade and low-carbon subsidy policies.

Few studies use game theory to simultaneously examine the mutual decision-making and emission reduction mechanisms for industries and enterprises from both micro and macro perspectives. Little information on combining product differentiation theory and emission reduction policies is available for the steel industry, and most information consists of narratives and policy descriptions. However, there are key differences in the production products of enterprises. The extent to which such differences affect overall production levels and the formulation of emission reduction policies requires additional analysis.

This paper constructs an improved two-stage dynamic game model by introducing an emission reduction policy and product differentiation concepts based on a carbon tax (Section 3). Next, this paper examines the influence of product differentiation on overall production using economic and CO_2 indexes (Section 4). Finally, this paper provides policy recommendations for the transformation and upgrading of the steel market and the formulation of emission reduction policies (Section 5).

3. Methods

3.1 Notations and explanations

According to the traditional regional division of China, China can be divided into six regions, namely, North China (i.e. Beijing, Tianjin, Hebei, Shanxi and Inner Mongolia); Northeast China (i. e. Liaoning, Jilin and Heilongjiang); East China (i.e. Shanghai, Jiangsu, Zhejiang, Anhui, Fujian, Jiangxi, Shandong and Taiwan); South Central China (i.e. Henan, Hubei, Hunan, Guangdong, Guangxi, Hainan, Hong Kong and Macau); Southwest China (i.e. Chongqing, Sichuan, Guizhou, Yunnan and Tibet); and Northwest China (i.e. Shaanxi, Gansu, Qinghai, Ningxia and Xinjiang) 1. For data reasons, Tibet, Hong Kong, Macau and Taiwan are not included here.

Here, this paper uses the inverse method to solve the two-stage game problem. Following Duan *et al.* (2017), this paper introduces "product differentiation degree (l_{ji})" and expand the notations and explanations (Table 1).

3.2 Establishment and game model analysis under product differentiation 2 conditions

The main body of the game includes the steel industry (government) and enterprises in the six regions. The production level of the enterprises represents the level of production in the region. The technical level indicators, such as CO_2 emission intensity of enterprises, represent the technology level.

The six regional oligopoly enterprises produce a product at the same time, and the products produced by each enterprise are substitutable but differ. The coefficient l_{ji} indicates the degree of substitutability of the enterprise j's product to enterprise i's product (substitution coefficient). The product takes the output as the decision variable, and achieves the balance of production and sales in one cycle. The set reduction scenario is the following: the carbon tax is the only emission

Notations	Explanations
Q	Steel production
P	The price of steel
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
$e_{2015,i}$	The region i CO_2 emission intensity of per ton steel in 2015
e_i	The region i CO_2 emission intensity of per ton steel at some stage
r_i	The decline range of CO_2 emission intensity of per ton steel in region i at some stage
R	The decline target of national CO_2 emission intensity of per ton steel at some stage
MAC	Marginal abatement cost curve in iron and steel industry
a_i	The quadratic coefficient of steel industry's MAC in region i
b_i	The primary coefficient of steel industry's MAC in region i
C_i	The cost function of steel industry in region i
$C_{0,i}$	The production cost of steel industry in region i
c_i	The cost of base period emission reduction in region i
T	The total carbon tax
t	The unit value of carbon tax
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
π_i	The profit function of steel industry in region i
E	The total CO_2 emissions in iron and steel industry
l_{ji}	The extent to which products produced by j can replace those produced by i

Table 1.
Notations and explanations used in this paper

reduction policy, and at a certain future time point K, the emission intensity decreases R from the CO_2 emission intensity in 2010. Because this paper only introduces the theory of product differentiation and bounded rationality based on a basic model, the model structure and main hypothesis do not differ from those of Duan *et al.* (2017).

The basic form of the profit function of each enterprise according to the Bowley model is as follows:

$$\pi_i = P(Q)q_i - C_iq_i = (\alpha - \beta Q)q_i - q_iC_{0,i} - q_i\lambda\left(c_i + \int_0^{r_i} MAC_i(r)dr\right) - te_iq_i$$

$$= (\alpha - \beta Q)q_i - q_iC_{0,i} - q_i\lambda\left(c_i + \int_0^{r_i} MAC_i(r)dr\right) - te_{2015,i}(1 - r_i)q_i \tag{1}$$

for which:

$$\pi_1 = [\alpha - \beta(q_1 + l_{21}q_2 + l_{31}q_3 + l_{41}q_4 + l_{51}q_5 + l_{61}q_6)]q_1 - \left(C_{0,1} + \lambda\left(c_1 + \int_0^{r_1} MAC_1(r)dr\right) + te_{2015,1}(1 - r_1)\right)q_1$$

$$\pi_2 = [\alpha - \beta(q_2 + l_{12}q_1 + l_{32}q_3 + l_{42}q_4 + l_{52}q_5 + l_{62}q_6)]q_2 - \left(C_{0,2} + \lambda\left(c_2 + \int_0^{r_2} MAC_2(r)dr\right) + te_{2015,2}(1 - r_2)\right)q_2$$

$$\pi_3 = [\alpha - \beta(q_3 + l_{13}q_1 + l_{23}q_2 + l_{43}q_4 + l_{53}q_5 + l_{63}q_6)]q_3 - \left(C_{0,3} + \lambda\left(c_3 + \int_0^{r_3} MAC_3(r)dr\right) + te_{2015,3}(1 - r_3)\right)q_3$$

$$\pi_4 = [\alpha - \beta(q_4 + l_{14}q_1 + l_{24}q_2 + l_{34}q_3 + l_{54}q_5 + l_{64}q_6)]q_4 - \left(C_{0,4} + \lambda\left(c_4 + \int_0^{r_4} MAC_4(r)dr\right) + te_{2015,4}(1 - r_4)\right)q_4$$

$$\pi_5 = [\alpha - \beta(q_5 + l_{15}q_1 + l_{25}q_2 + l_{35}q_3 + l_{45}q_4 + l_{65}q_6)]q_5 - \left(C_{0,5} + \lambda\left(c_5 + \int_0^{r_5} MAC_5(r)dr\right) + te_{2015,5}(1 - r_5)\right)q_5$$

$$\pi_6 = [\alpha - \beta(q_6 + l_{16}q_1 + l_{26}q_2 + l_{36}q_3 + l_{46}q_4 + l_{56}q_5)]q_6 - \left(C_{0,6} + \lambda\left(c_6 + \int_0^{r_6} MAC_6(r)dr\right) + te_{2015,6}(1 - r_6)\right)q_6$$

$$\tag{2}$$

In equations (1) and (2), $P = \alpha - \beta Q$ is the market inverse demand function faced by steel enterprises and q_i is the amount of product produced by each enterprise. The cost function of an enterprise C_i is related to the reduction emission intensity. r_i is the emission reduction range selected by enterprise i. e_i is the CO_2 emission intensity of enterprise i.

Let $\frac{\partial \pi_i}{\partial q_i} = 0$ and $\frac{\partial \pi_i}{\partial r_i} = 0$ and the corresponding reduction range of emission intensity r_i and output q_i of steel enterprises in each region can be obtained.

Under the carbon tax value t, when the output of each enterprise is q_i and the CO_2 emission intensity is e_i, the total carbon tax revenue is $T_i = \sum_{i=1}^{6} te_iq_i = \sum_{i=1}^{6} te_{2015,i}(1 - r_i)q_i$, the external macroscopic loss caused by CO_2 emissions to the environment is $D(E) = \theta E = \theta\sum_{i=1}^{6} e_iq_i = \theta\sum_{i=1}^{6} e_{2015,i}(1 - r_i)q_i$, and thus:

$$W = CS + PS + T - D(E) = \int_0^Q P(q)dq - P(Q)Q + \sum_{i=1}^{6}\pi_i + \sum_1^{6}T_i - \theta E$$

$$= \int_0^Q (\alpha - \beta q)dq - \left(\alpha - \beta\sum_{i=1}^{6}q_i\right)\sum_{i=1}^{6}q_i + \sum_{i=1}^{6}\pi_i$$

$$+ \sum_{i=1}^{6}te_{2015,i}(1 - r_i)q_i - \theta\sum_{i=1}^{6}e_{2015,i}(1 - r_i)q_i \tag{3}$$

In equation (3),$CS = \int_0^Q P(q)dq - P(Q)Q$ stands for the consumer surplus and $PS = \sum_{i=1}^{6} \pi_i$ stands for the producer surplus.

The regional enterprises obtain the profit function of the enterprise by selecting the decline in emission intensity and production output as a response to the government's corresponding emission reduction policy and emission reduction target R. The government's decision can be expressed as:

$$\begin{aligned} &\max W \\ &s.t. \begin{cases} \dfrac{\displaystyle\sum_{i=1}^{6} e_{2015,i}(1-r_i)q_i}{\displaystyle\sum_{i=1}^{6} q_i} = e_{2010}(1-R) \\ 0 < r_i < 1 \\ e_i > 0 \\ q_i > 0 \\ t \geq 0 \\ i = 1,2,3,4,5,6 \end{cases} \end{aligned} \qquad (4)$$

In Section 4, this paper will analyze the changes in the economic and environmental indicators of the entire steel industry and each enterprise when the products produced by each enterprise are the same ($l = 1$), different ($l \neq 1$) and varying in the degree of product differentiation.

3.3 Data sources
The statistics in this study were obtained from the China Statistical Yearbook (2005–2017), China Industrial Statistical Yearbook (2005–2017), China Energy Statistical Yearbook (2005–2017), China Steel Yearbook (2005–2017) and statistical yearbooks of various provinces. The economic data were equivalent to comparable prices in 2010. The period was from 2005 to 2016. CO_2 emissions in industrial production (IPPU CO_2) were included in this paper, a source of large amounts of CO_2.

Because of the available data, the iron and steel industry's relevant energy consumption and economic data were derived from the ferrous metal smelting and calendering processing industry in the statistical yearbook. The CO_2 accounting of fossil energy consumption and IPPU refer to IPCC (2006) and Duan *et al.* (2016).

3.4 Parameter fitting
The inverse demand curve can be approximated as a straight line inclined to the lower right. According to the calculation, the inverse demand curve fitting equation is as follows:

$$P = \alpha - \beta Q = 15769.56 - 1.13 \times 10^{-5}Q \qquad (5)$$

In 2010, the average level of CO_2 emissions was 3.1710 tons of CO_2 per ton of steel [3] (the same below, omitted). In the calculation, the base period data of each region was for 2015. The average level of CO_2 emission in 2015 was 2.8210. The CO_2 emission levels of the six regions in 2015 are shown in Table 2.

Notations	Unit		$i=1$	$i=2$	$i=3$	$i=4$	$i=5$	$i=6$
e_{2015i}	tCO_2/t		2.3344	3.5698	2.9040	2.8779	3.2202	4.5864
a_i			11661	17208	16932	12952	6397	3485
b_i			−169.76	8876.70	−166.92	1483.60	502.52	421.13
c_i	Yuan		2168.20	3511.10	2165.40	3325.10	2368.70	3814.30
$C_{O,i}$	Yuan	2015	2833.15	4898.47	3453.53	4153.15	3799.03	3832.38
		2020	2124.86	3918.77	2590.15	2491.89	3609.08	3640.76

Table 2.
Some parameter
values

The calculation method reference was based on Färe *et al.* (2007) and Lee *et al.* (2002) (the data were updated to 2016, and the function form was slightly changed) and the quadratic form was selected as the marginal abatement cost curve (MACC) regression equation. The relationship between the emission intensity reduction in each region and the CO_2 MACC is shown in Table 2. This paper used $\lambda \left(c_i + \int_0^{r_i} MAC_i(r)dr \right)$ to represent the actual emission reduction cost – and λ is 0.5 – to minimize the error.

This paper referred to the target of reducing the comprehensive energy consumption of a ton of steel by 12kgce in 2020 to set the CO_2 emission intensity reduction target [Steel Industry Adjustment and Upgrade Plan (2016–2020)]. The target for 2020 was approximately 85% of the energy consumption level in 2010. Therefore, this paper sets the CO_2 emission intensity in 2020 to be 15% lower than that in 2010 [4]. The output, profit and emission intensity of enterprises and the industry were examined when the emission reduction target was 15%–20%. This paper assumed that by 2020, the production costs in North China, East China and South Central China will decrease significantly, while the production costs in Northeast China, Southwest China and Northwest China will decrease less. External macro-environmental loss parameters by CO_2 emissions are based on Guenno and Tiezzi (1998) and $\theta = 14.55$ Yuan/ton CO_2. The specific data simulation parameter settings are shown in Table 2.

4. Results and discussion

4.1 Each enterprise produces the same product
When the products produced in each region are the same and can be completely replaced. At this time, to achieve the greatest social welfare, when the emission reduction targets increase from 15% to 20%, the unit carbon tax increases from 12.47 Yuan/ton CO_2 to 34.24 Yuan/ton CO_2 and the total carbon tax increases nearly by 1.57 times. Total output, total social welfare (W), consumer surplus (CS), producer surplus (PS) and CO_2 emissions decrease. The total output is maintained at 846–851 million tons, a decrease of more than 25% compared with the total production of 1.135 billion tons in 2016. This finding indicates that the steel demand needs to decrease in 2020 significantly to maximize social welfare. As the emission reduction target increases from 15% to 20%, total output, W, CS, PS, and CO_2 emission loss decrease by 0.57%, 0.06%, 1.13%, 0.23% and 6.41%, respectively.

To achieve the reduction target (15%–20%), the enterprises in each region need to reduce emission intensity and production. When the emission reduction targets gradually increased, the decline rate in emission intensity in various regions increased. The emission intensity of Southwest China and Northwest China decreased the most. When the industry emission reduction target was 20%, the emission reduction rate in Northwest China was the largest at 24.58%. The emission reductions in East China and North China were moderate (7%–12%). The emission reduction range in the Northeast and South Central regions was small and that in the Northeast was the smallest. Because of the different costs and emission reduction intensities, the addition of a carbon tax, under gradual increases in emission reduction targets, results in a decrease in the production in other regions, with the exception of the increase in output in North China (by 0.03 billion tons). The Northeast and Northwest showed significant declines, with yields decreasing by 5% or more. The results are shown in Tables 3 and 4, as well as Figures 1 and 2.

4.2 Each enterprise produces different products
To facilitate calculation and discussion, the substitution coefficient of the products between enterprises was the same (i.e. $l_{ji} = l$), and the value of l was 0.95 when the product was characterized by differentiation. This case was similar to the same product scenario: when

the emission reduction target increased from 15% to 20%, the unit carbon tax and total carbon tax also increased. The unit tax value increased from 15.35 Yuan/ton to 38.19 Yuan/ton, and the total carbon tax increased by 1.33 times. Total production, total social welfare (W), consumer surplus (CS), producer surplus (PS) and CO_2 emissions losses decreased. The total output was stable at approximately 877–882 million tons. As the emission reduction target increased from 15% to 20%, total output, W, CS, PS and macro-environmental losses from CO_2 emissions decreased by 0.59%, 0.12%, 1.17%, 0.36% and 6.43%, respectively.

Similar to the same product scenario, the rate of decline in emission intensity in various regions increased when the emission reduction targets increased. The emission intensity of Southwest China and Northwest China decreased the most. When the industry emission reduction target was 20%, the Northwest China emission reduction rate was the highest (26.23%); the emission reduction range in East and North China was moderate, and the decline was 7.76%–13.12%. Emission reductions in Northeast and South Central China were low, and those in the Northeast were the lowest. When emission reduction targets increased, the output of the regions decreased, with the exception of the increase in output in North

Emission reduction target	15%	16%	17%	18%	19%	20%
Carbon tax value (Yuan)	12.47	16.04	20	24.35	29.10	34.24
Production (100 million tons)	8.5127	8.5046	8.4957	8.4861	8.4757	8.4646
Rate of change, production(with 15% as the base)	–	−0.10%	−0.20%	−0.31%	−0.44%	−0.57%
Rate of change, social welfare (with 15% as the base)	–	−0.01%	−0.01%	−0.02%	−0.04%	−0.06%
Rate of change, producer surplus (with 15% as the base)	–	−0.04%	−0.08%	−0.12%	−0.17%	−0.23%

Table 3.
The changes of the overall industry indicators under the carbon tax mechanism, the emission reduction target is 15%−20%

Emission reduction target		15%	16%	17%	18%	19%	20%
Production (100 million tons)	North China	2.5789	2.5796	2.5803	2.5810	2.5817	2.5825
	Northeast China	0.3823	0.3808	0.3793	0.3776	0.3758	0.3740
	East China	2.1623	2.1621	2.1619	2.1617	2.1614	2.1612
	South Central China	1.7354	1.7351	1.7348	1.7345	1.7341	1.7337
	Southwest China	1.1672	1.1666	1.1660	1.1654	1.1648	1.1641
	Northwest China	0.4867	0.4845	0.4823	0.4801	0.4778	0.4755
Rate of change, production(with 15% as the base)	North China	–	0.05%	0.11%	0.17%	0.23%	0.30%
	Northeast China	–	−0.79%	−1.69%	−2.71%	−3.83%	−5.08%
	East China	–	−0.02%	−0.04%	−0.06%	−0.09%	−0.12%
	South Central China	–	−0.03%	−0.08%	−0.12%	−0.17%	−0.23%
	Southwest China	–	−0.10%	−0.21%	−0.32%	−0.44%	−0.57%
	Northwest China	–	−0.88%	−1.81%	−2.78%	−3.77%	−4.77%
The decline range of emission intensity (with data in 2015 as the base)	North China	−7.83%	−8.77%	−9.71%	−10.63%	−11.55%	−12.46%
	Northeast China	−0.98%	−1.26%	−1.56%	−1.89%	−2.24%	−2.62%
	East China	−7.05%	−7.93%	−8.79%	−9.65%	−10.50%	−11.34%
	South Central China	−3.67%	−4.47%	−5.30%	−6.15%	−7.01%	−7.87%
	Southwest China	−7.95%	−9.37%	−10.80%	−12.21%	−13.63%	−15.05%
	Northwest China	−13.06%	−15.37%	−17.68%	−19.98%	−22.28%	−24.58%

Table 4.
The changes of the various region enterprise indicators under the carbon tax mechanism, the emission reduction target is 15%−20%

China (an increase of 69 million tons). The output in Northeast China and Northwest China decreased significantly by 4.24% and 3.94%, respectively.

Compared with the case of implementing the carbon tax policy and producing the same product, the general pattern of the results was consistent with the same product scenario when the products were different. However, under the same emission reduction target, the carbon tax, total carbon tax, total social welfare, output, producer surplus and consumer

Figure 1.
The rate of change of output, social welfare and producer surplus under the carbon tax mechanism, take 15% as the baseline
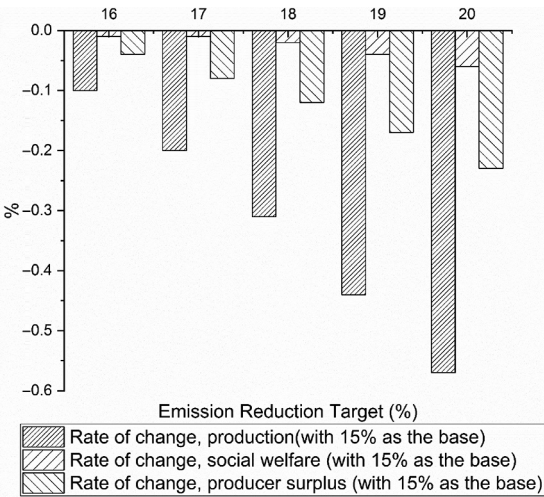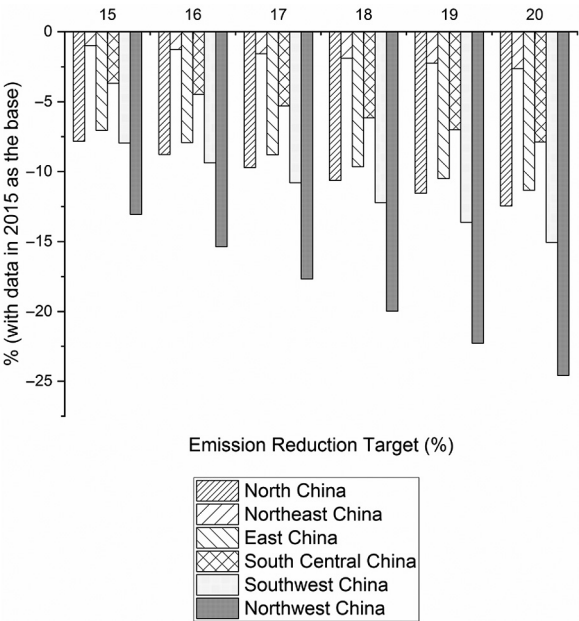

Figure 2.
The change of regional emission intensity with the overall emission reduction target (15%–20%, carbon tax scenario only)

surplus of products under the condition of greater product differentiation, the increase or decrease in rates of change is larger than for when the product is the same. The results are shown in Tables 5 and 6.

When l takes other values, conclusions are largely the same.

4.3 The substitution coefficient is variable
When the product is differentiated and the substitution coefficient of the products between enterprises is the same (i.e. $l_{ji} = l$), the values of l are 0.95, 0.90, 0.85, 0.80 and 0.75 ($R = 15\%$) and the other parameters are consistent with the same product scenario. In this section, changes in the various parameter are studied ($R = 15\%$) when $l = 0.95$, 0.90, 0.85, 0.80 and 0.75.

Under the same industry emission reduction targets and with a gradual reduction of the substitution coefficient, the total social welfare (W), consumer surplus (CS), producer surplus (PS), the unit carbon tax, total carbon tax, total output and CO_2 emission loss increased. The trend is shown in Table 7 and Figure 3. The carbon tax value increased from

Emission reduction target	15%	16%	17%	18%	19%	20%
Carbon tax value (Yuan)	15.35	19.16	23.36	27.93	32.87	38.19
Production (100 million tons)	8.8212	8.8123	8.8026	8.7922	8.7812	8.7694
Rate of change, production (with 15% as the base)	–	−0.10%	−0.21%	−0.33%	−0.45%	−0.59%
Rate of change, social welfare (with 15% as the base)	–	−0.02%	−0.04%	−0.06%	−0.09%	−0.12%
Rate of change, producer surplus (with 15% as the base)	–	−0.06%	−0.12%	−0.20%	−0.27%	−0.36%

Table 5.
The changes of the overall industry indicators under the carbon trade mechanism, the emission reduction target is 15%−20%, the substitution coefficient is 0.95

Emission reduction target		15%	16%	17%	18%	19%	20%
Production (100 million tons)	North China	2.5772	2.5784	2.5797	2.5811	2.5826	2.5841
	Northeast China	0.4818	0.4785	0.4749	0.4708	0.4663	0.4614
	East China	2.1790	2.1785	2.1779	2.1772	2.1764	2.1756
	South Central China	1.7723	1.7716	1.7707	1.7697	1.7686	1.7674
	Southwest China	1.2307	1.2294	1.2281	1.2266	1.2251	1.2236
	Northwest China	0.5802	0.5759	0.5714	0.5667	0.5620	0.5573
Rate of change, production	North China	–	0.05%	0.10%	0.15%	0.21%	0.27%
(with 15% as the base)	Northeast China	–	−0.68%	−1.44%	−2.29%	−3.33%	−4.24%
	East China	–	−0.02%	−0.05%	−0.08%	−0.12%	−0.16%
	South Central China	–	−0.04%	−0.09%	−0.15%	−0.21%	−0.28%
	Southwest China	–	−0.10%	−0.21%	−0.33%	−0.45%	−0.58%
	Northwest China	–	−0.74%	−1.52%	−2.31%	−3.12%	−3.94%
The decline range of emission	North China	−8.60%	−9.52%	−10.43%	−11.33%	−12.22%	−13.11%
intensity (with data in 2015 as	Northeast China	−1.21%	−1.50%	−1.82%	−2.16%	−2.52%	−2.91%
the base)	East China	−7.77%	−8.61%	−9.46%	−10.29%	−11.12%	−11.95%
	South Central China	−4.32%	−5.13%	−5.96%	−6.80%	−7.65%	−8.50%
	Southwest China	−9.11%	−10.51%	−11.90%	−13.29%	−14.68%	−16.07%
	Northwest China	−14.95%	−17.21%	−19.48%	−21.74%	−23.98%	−26.23%

Table 6.
The changes of the various region enterprise indicators under the carbon trade mechanism, the emission reduction target is 15%−20%, the substitution coefficient is 0.95

¥15.35 to ¥25.44, the total carbon tax increased by 94.04%, the total output increased from 882 million tons to 1.033 billion tons, and the emission loss increased by 17.08%.

Under the same industry emission reduction target for each sub-region and the gradual reduction of the substitution coefficient, the output, profit and emission reduction range increased (Figures 4–6).

Similar results were obtained when R was set to other values. This finding suggests that the production of differentiated products can promote economic performance compared with the same product. Generally, greater degrees of product differentiation have greater promoting effects on economic performance.

4.4 Discussion

In Chapter 4, this paper discussed the situation of different degrees of differentiation of steel products, observed the changing trends in economic and environmental indicators, and discussed differences among regions. In fact, by modifying the value of some parameters or parts of the framework of the model, the macro product game model established in this paper can be used to change comparisons in the degree of differentiation of other products and can also be applied to other industries, reflecting the generality of the model.

Based on the assumptions in the model construction process, the limitations of this model arise from the partially idealized theoretical framework, which slightly differs from the conditions of actual production. For example, the price function, production function and MACC are mostly linear functions that may differ from actual functions.

Table 7.
The changes of various indicators under different substitution coefficient

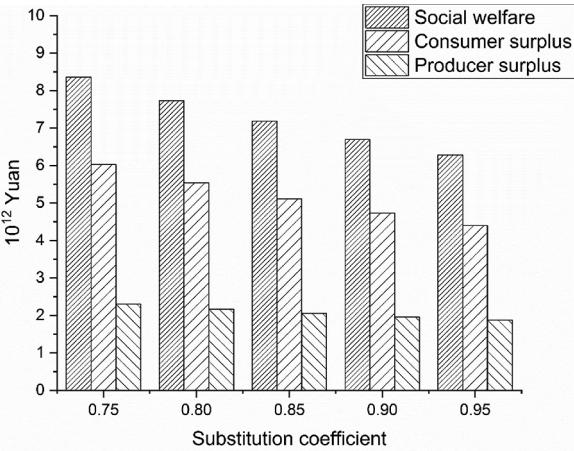| Substitution coefficient	0.95	0.90	0.85	0.80	0.75
Carbon tax value (Yuan)	15.35	18.10	20.69	23.14	25.44
Production (100 million tons)	8.8212	9.1538	9.5135	9.9035	10.3279
Social welfare (10^{12} Yuan)	6.2758	6.6977	7.1794	7.7299	8.3599
Consumer surplus (10^{12} Yuan)	4.3965	4.7343	5.1136	5.5415	6.0267
Producer surplus (10^{12} Yuan)	1.8774	1.9547	2.0501	2.1654	2.3029

Figure 3.
Comparison of social welfare, consumer surplus and producer surplus under different substitution coefficients
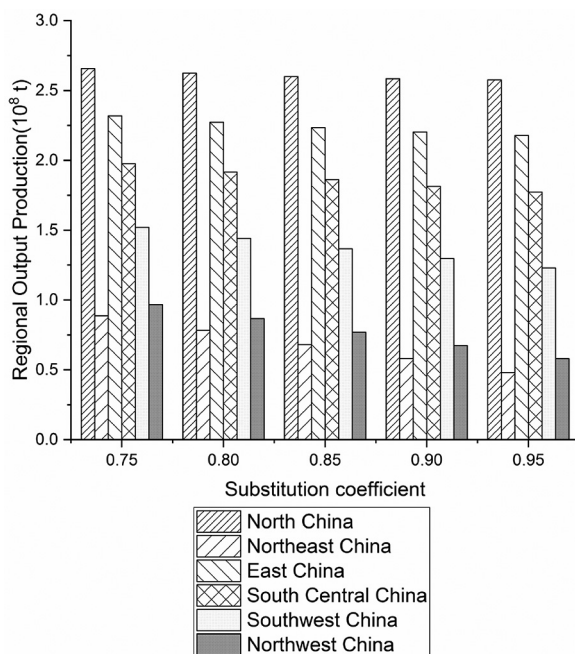
Figure 6.
Variation of regional
emission intensity
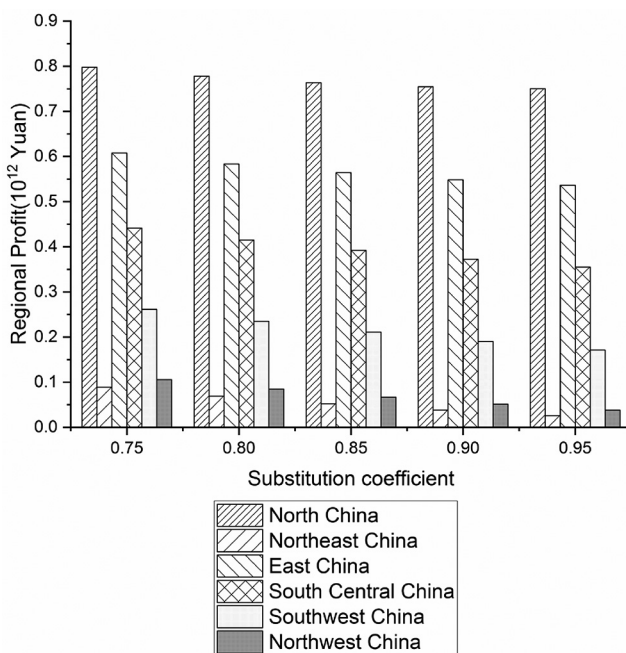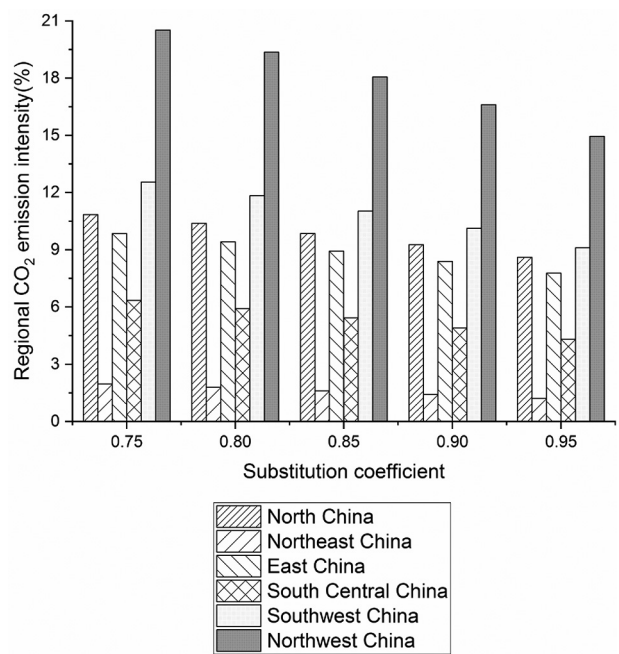under different
substitution
coefficients

However, this observation does not affect the theoretical significance of the model construction ideas nor change trends in the future actual operation process. Because this paper established a macro game model based on macro statistical data, the results and changing trends in the indicators were calculated and analyzed based on previous data, which can be dynamically adjusted continuously. In addition, this paper only analyzed the implementation of carbon tax policy and product differentiation policy in China's steel industry. As relevant policies continuously improve in the future, subsidies policies, carbon trading policies and other economic and environmental policies will also be included in the scope of research. This study supplies theoretical ideas and references for this purpose.

5. Conclusions

This paper established a two-stage multi-oligopoly enterprise production selection model by introducing a carbon tax policy and product differentiation theory. The changes in the total output, social welfare and other indicators under the constraints of the industry's emission reduction targets and emission reduction policies were analyzed. The effects of product differentiation degree on the decline in output and emission intensity of each enterprise, as well as other economic factors, were also analyzed. The main conclusions are detailed below.

Regardless of whether there is a difference in the products produced among the enterprises, the unit carbon tax and total carbon tax always increased as the CO_2 emission reduction targets increased; in contrast, the industry social welfare (W), consumer surplus (CS), external macro-environmental losses and total production decreased. CO_2 emission reduction pressure among regional oligarchic enterprises increased. The emission reduction rates in the Northwest and Southwest regions were higher than those in other regions; the

oligarchic enterprises in North China, East China and South Central China were second; and emission reduction rates were least in the Northeast. When there were product differences, along with increases in emission reduction targets, the rate of change of the indicators increased. When the emission reduction target was unchanged and the substitution coefficient decreased, the indexes tended to increase.

Because the steel industry is relatively large but not strong, duplicated production is widespread, and the problem of homogenization is serious, the steel industry should improve the effective supply level of steel and increase the differentiation of products to ensure the demand for infrastructure. Additional support is needed for the research, development and industrialization of high-end steel products required for major technical equipment in high-tech ships, marine engineering equipment, advanced rail transit, electric power, aerospace, machinery and other fields.

Even if products are differentiated, production and consumption are lower when a market equilibrium is reached. Thus, the steel industry needs to defuse excess capacity, prohibit new production capacity and push "zombie" enterprises to exit the market in the future. By implementing a carbon tax and other emission reduction policies and market mechanisms, as well as formulating mandatory emission reduction standards and energy consumption indicators, government departments can promote supply-side structural reform of the iron and steel industry.

As noted in Section 4.4, the game model constructed in this study has certain limitations that should be considered and be improved by future research. At the same time, future research should further explore the impact of environmental policies and product differentiation policies on other industrial sectors.

Notes

1. According to the characteristics of statistical data, this study 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 study, product differentiation specifically refers to the degree of substitution between products in the macroscopic sense. Because of the lack of micro engineering data of enterprises in various regions, this paper only analyzed the macro-economic and environmental impacts changes under different scenarios. The differences in input factors, product quality and product type in the production process are not discussed in this paper.

3. In this study, all data are macro from the statistical yearbook and other statistical material. Currently, China still lacks production and consumption data of all enterprises in each region. Therefore, the emission intensity, output and other data in this study are based on the macro statistical data or the average value for each region.

4. At present, the CO_2 emission reduction targets are currently not specified in China's steel industry development plan, only the energy intensity reduction target is mentioned. Therefore, this paper selects the target of energy intensity reduction of 15% to represent the approximate CO_2 emission reduction target, although the two are not exactly the same.

References

Altug, M.S. (2016), "Supply chain contracting for vertically differentiated products", *International Journal of Production Economics*, Vol. 171, pp. 34-45.

Benavente, J.M.G. (2016), "Impact of a carbon tax on the Chilean economy: a computable general equilibrium analysis", *Energy Economics*, Vol. 57, pp. 106-127.

Bowley, A.L. (1924), *The Mathematical Groundwork of Economics: An Introductory Treatise*, Clarendon Press, Oxford.

Cao, K.Y., Xu, X.P., Wu, Q. and Zhang, Q.P. (2017), "Optimal production and carbon emission reduction level under cap-and-trade and low carbon subsidy policies", *Journal of Cleaner Production*, Vol. 167, pp. 505-513.

Chang, M.H. (1991), "The effects of product differentiation on collusive pricing", *International Journal of Industrial Organization*, Vol. 9 No. 3, pp. 453-469.

Chen, W., Zhou, J.F., Li, S.Y. and Li, Y.C. (2017), "Effects of an energy tax (carbon tax) on energy saving and emission reduction in Guangdong province-based on a CGE model", *Sustainability*, Vol. 9 No. 5, p. 681.

Choi, T.M. (2013), "Optimal apparel supplier selection with forecast updates under carbon emission taxation scheme", *Computers and Operations Research*, Vol. 40 No. 11, pp. 2646-2655.

Duan, Y., Mu, H.L. and Li, N. (2016), "Analysis of the relationship between China's IPPU CO_2 emissions and the industrial economic growth", *Sustainability*, Vol. 8 No. 5, p. 426.

Duan, Y., Li, N., Mu, H.L. and Gui, S.S. (2017), "Research on CO_2 emission reduction mechanism of China's iron and steel industry under various emission reduction policies", *Energies*, Vol. 10 No. 12, p. 2026.

Färe, R., Grosskopf, S. and Pasurka, C.A. (2007), "Environmental production functions and environmental directional distance functions", *Energy*, Vol. 32 No. 7, pp. 1055-1066.

Feng, L. (2012), "Research on development model of steel enterprise on condition of financial crisis evening – discussion on development model of ma steel", Master thesis, Anhui University of Technology, Maanshan.

Fu, X., Dresner, M. and Oum, T.H. (2011), "Effects of transport service differentiation in the US domestic airline market", *Transportation Research Part E: Logistics and Transportation Review*, Vol. 47 No. 3, pp. 297-305.

Gao, H.C. and Lou, C.W. (2012), "The reflection and adjustment of the development strategy for steel industry of China during the period of the twelfth five-year plan", *China Soft Science*, Vol. 6, pp. 6-14.

Gautier, L. (2014), "Policy reform of emission taxes and environmental research and development incentives in an international Cournot model with product differentiation", *Environment and Development Economics*, Vol. 19 No. 4, pp. 440-465.

Gebauer, H., Gustafsson, A. and Witell, L. (2011), "Competitive advantage through service differentiation by manufacturing companies", *Journal of Business Research*, Vol. 64 No. 12, pp. 1270-1280.

Goldberg, P.K. (1995), "Product differentiation and oligopoly in international markets: the case of the U. S. Automobile industry", *Econometrica*, Vol. 63 No. 4, pp. 891-951.

Goto, N. (1995), "Macroeconomic and sectoral impacts of carbon taxation: a case for the Japanese economy", *Energy Economics*, Vol. 17 No. 4, pp. 277-292.

Govinda, R.T. and Ram, M.S. (2002), "General equilibrium analysis of economic and environmental effects of carbon tax in a developing country: case of Thailand", *Environmental Economics and Policy Studies*, Vol. 5 No. 3, pp. 179-211.

Grant, A., Patrizio, L., Peter, M. and Kim, S. (2014), "The economic and environmental impact of a carbon tax for Scotland: a computable general equilibrium analysis", *Ecological Economics*, Vol. 100, pp. 40-50.

Gregmar, I.G. and Jonathan, K.Y. (2010), "An integrated tax-subsidy policy for carbon emission reduction", *Resource and Energy Economics*, Vol. 32 No. 3, pp. 310-326.

Guenno, G. and Tiezzi, S. (1998), *The Index of Sustainable Economics Welfare (ISEW) for Italy*, Fondazione Eni Enrico Mattei, Milano.

Guo, Z.Q., Liu, H.B. and Niu, D.X. (2012), "Simulation analysis on China carbon tax policy affected to energy and carbon dioxide emission base on CGE model", *Coal Engineering*, Vol. 1, pp. 138-140.

Helen, C., Paul, K. and Erwin, C. (2015), "Modelling the impact of energy policies on the Philippine economy: carbon tax, energy efficiency, and changes in the energy mix", *Economic Analysis and Policy*, Vol. 8, pp. 222-237.

Hotelling, H. (1929), "Stability in competition", *The Economic Journal*, Vol. 39 No. 153, pp. 41-57.

IPCC (Intergovernmental Panel on Climate Change) (2006), *IPCC Guidelines for National Greenhouse Gas Inventories*, IPCC, Bracknell.

Krass, D., Nedorezov, T. and Ovchinnikov, A. (2013), "Environmental taxes and the choice of green technology", *Production and Operations Management*, Vol. 22 No. 5, pp. 1035-1055.

Kugler, M. and Verhoogen, E. (2012), "Prices, plant size and product quality", *The Review of Economic Studies*, Vol. 79 No. 1, pp. 307-339.

Lee, J.D., Park, J.B. and Kim, T.Y. (2002), "Estimation of the shadow prices of pollutants with production/environment inefficiency taken into account: a nonparametric directional distance function approach", *Journal of Environmental Management*, Vol. 64 No. 4, pp. 365-375.

Li, X.C. (2015), "The transformation and innovation development strategy of Chinese iron and steel enterprises under the new normal", *Land and Resources Information*, Vol. 10, pp. 15-21.

Li, W. and Chen, J. (2018), "Pricing and quality competition in a brand-differentiated supply chain", *International Journal of Production Economics*, Vol. 202, pp. 97-108.

Li, Y.Z. and Su, B. (2017), "The impacts of carbon pricing on coastal megacities: a CGE analysis of Singapore", *Journal of Cleaner Production*, Vol. 165 No. 1, pp. 1239-1248.

Li, C., Wang, L.P. and Ren, R.M. (2005), "Product differentiation and competitiveness– a case study of the textile and garment industry", *Business Economics and Administration*, Vol. 3, pp. 37-41.

Ling, T., Shi, J.R., Yu, L. and Qin, B. (2017), "Economic and environmental influences of coal resource tax in China: a dynamic computable general equilibrium approach", *Resources, Conservation and Recycling*, Vol. 117, pp. 34-44.

Ma, L. (2005), "Silicon steel products difference strategic research of WISCO", Master thesis, Wuhan University, Wuhan.

Mann, R.F. (2009), "The case for the carbon tax: how to overcome politics and find our green destiny", *Environmental Law Reporter*, Vol. 39, pp. 10118-10126.

Meng, X.G., Yao, Z., Nie, J.J., Zhao, Y.X. and Li, Z.L. (2018), "Low-carbon product selection with carbon tax and competition: effects of the power structure", *International Journal of Production Economics*, Vol. 200, pp. 224-230.

Ouchida, Y. and Goto, D. (2014), "Do emission subsidies reduce emission? In the context of environmental R and D organization", *Economic Modelling*, Vol. 36, pp. 511-516.

Poyago-Theotoky, J.A. (2007), "The organization of R&D and environmental policy", *Journal of Economic Behavior and Organization*, Vol. 62 No. 1, pp. 63-75.

Qian, Z.J. (2016), "An analysis of the impacts of a carbon tax on energy and economy in Zhejiang province", Master thesis, North China Electric Power University, Beijing.

Qiao, H., Song, N. and Gao, H.W. (2014), "Analysis on the strategies of European union's airline carbon tax with stackelberg game models", *Systems Engineering - Theory and Practice*, Vol. 34, pp. 158-167.

Qiao, J.S., Zhang, P. and Li, Q. (2018), "Research on the path and countermeasures of reducing capacity, adjusting structure and seeking development in the steel industry", *Journal of Xingtai University*, Vol. 33 No. 4, pp. 82-86.

Shaked, A. and Sutton, J. (1982), "Relaxing price competition through product differentiation", *The Review of Economic Studies*, Vol. 49 No. 1, pp. 3-13.

Shi, M.J., Yuan, Y.N., Zhou, S.L. and Li, N. (2013), "Carbon tax, cap-and-trade or mixed policy: which is better for carbon mitigation?", *Journal of Management Sciences in China*, Vol. 16 No. 9, pp. 9-19.

Shubik, M. and Levitan, R. (1980), *Market Structure and Behavior*, Harvard University Press, Cambridge.

Tim, C., Sean, L. and Susan, S. (2009), "The distributional implications of a carbon tax in Ireland", *Energy Policy*, Vol. 37 No. 2, pp. 407-412.

Wang, W.X. (2017), "Discussion on product structure management", *China Steel Focus*, Vol. 5, pp. 39-41.

Wang, F., Chen, J.G., Liu, J., Lin, X.Y. and Chen, S. (2017), "Effect of carbon tax on macro-economy and carbon emission reduction in Jiangsu province: simulation analysis based on CGE model", *Ecological Economy*, Vol. 33 No. 9, pp. 31-36.

Wissema, W. and Dellink, R. (2007), "AGE analysis of the impact of a carbon energy tax on the Irish economy", *Ecological Economics*, Vol. 61 No. 4, pp. 671-683.

Wu, L.Y., Wang, Z., Xu, C.J. and Yan, Y.M. (2016), "A CGE model for provincial carbon economy: a case study of Henan province", *Geographical Research*, Vol. 35 No. 5, pp. 941-952.

Xu, X.Y., Xu, X.P. and He, P. (2016), "Joint production and pricing decisions for multiple products with cap-and-trade and carbon tax regulations", *Journal of Cleaner Production*, Vol. 112, pp. 4093-4106.

Yahoo, M. and Othman, J. (2017), "Employing a CGE model in analysing the environmental and economy-wide impacts of CO_2 emission abatement policies in Malaysia", *Science of the Total Environment*, Vols 584/585, pp. 234-243.

Yakita, A. and Yamauchi, H. (2011), "Environmental awareness and environmental R&D spillovers in differentiated duopoly", *Research in Economics*, Vol. 65 No. 3, pp. 137-143.

Yang, L. (2009), "Research on the coordination of cooperation in tourism supply chain based on product differentiation", phD thesis, Nanjing University of Aeronautics and Astronautics, Nanjing.

Yu, W.S. and Zhang, Z.Y. (2013), "Feasibility and mode selection of carbon tax policy in China based on game theory", *China Population, Resources and Environment*, Vol. 6, pp. 8-15.

Yu, X.F. (2018), "Discussion on cost control of new product research and development in iron and steel enterprises", *Metallurgical Financial Accounting*, Vol. 37 No. 12, pp. 37-39.

Zhu, J.C. (2015), "The impact of carbon tax on regional; Economic-Environment-Energy system", Master thesis, North China Electric Power University, Beijing.

Further reading

China Iron and Steel Association (2020), *China Steel Yearbook 2005–2017*, The Editorial Board of China Steel Yearbook, Beijing.

NBS (National Bureau of Statistics of the People's Republic of China) (2020a), *China Statistical Yearbook 2005-2017*, National Bureau of Statistics of the People's Republic of China, Beijing.

NBS (National Bureau of Statistics of the People's Republic of China) (2020b), *China Industrial Economy Statistical Yearbook 2005-2017*, National Bureau of Statistics of the People's Republic of China, Beijing.

NBS (National Bureau of Statistics of the People's Republic of China) (2020c), *China Energy Statistical Yearbook 2005-2017*, National Bureau of Statistics of the People's Republic of China, Beijing.

About the authors

Ye Duan obtained bachelor's degree and doctorate from Dalian University of Technology in 2008 and 2018, respectively. He is mainly engaged in multi-disciplinary research on energy, economic, environment policy, CO_2 emission reduction policy and industrial geography. Ye Duan is the corresponding author and can be contacted at: dydl@lnnu.edu.cn

Zenglin Han is Professor and doctoral supervisor. He obtained bachelor's degree from Northeast Normal University in 1982. In 1986, he graduated with a master's degree in Human Geography from Northeast Normal University. In 2003, he graduated from Northeast Normal University, majoring in Economic Geography with a doctorate degree. He is mainly engaged in the teaching and research of humanities-economic geography, and he has long been engaged in the research of transportation geography, industrial geography and regional marine economic geography.

Hailin Mu is Professor and doctoral supervisor. He obtained PHD from Dalian University of Technology in 1994, and PhD in Engineering from the National Saitama University in Japan in 2002. His main research areas are energy and environmental development strategies, energy conservation and emission reduction technologies, policies and countermeasures, industrial greenhouse gas emission reduction technologies and low carbon development mechanisms.