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Research

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Cost and Welfare: A Simulation of Establishing A Unified Carbon Market in China

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Abstract

Background

Global warming has aroused wide concern of international community, which has reached a consensus on the carbon abatement. In 2017, China should have established a unified market for carbon emission trading, while the government has postponed the establishment because the uncertainty of cost calculation and welfare. Therefore, the cost and welfare of carbon abatement in simulated scenarios could help the government in establishing a unified carbon market and setting suitable policy. In the national carbon trading market, the variations of different abatement cost are the precondition of carbon exchange. This paper set forth theories related to carbon market and used parametric directional distance function model to derive the shadow prices of 30 provinces from 2011 to 2017. Then the classic logarithmic model is used to simulate marginal abatement cost curves, which is further applied to empirically investigate the welfare of 30 provinces in two scenarios of carbon trading market in China.

Results

The results indicate that marginal abatement cost would rise with the increasing of emission reduction and vary significantly among provinces, and undeveloped provinces have greater potential in emission reduction than developed regions. Moreover, all provinces could benefit from the establishment of the nationwide ETS.

Conclusions

This article combines the theoretical model of shadow prices with the analysis of China's carbon trading market in an attempt to analyze the cost and welfare of Chinese provinces and cities on the unified carbon trading market, adding the time trend factor to the directional distance function, and then further combines the parameter method to estimate the shadow price of CO₂. Finally, the paper gives some proposals regarding to China's ETS and carbon reduction targets.

Keywords: cost and welfare; marginal abatement cost; directional distance function; carbon trading market

Background

Environmental concerns and issues, especially climate change, are moving from the realm of corporate environment, health, and safety personnel, into that of community of shared future for mankind. Putting a price on greenhouse gas emissions on country and company bottom lines will have a significant effect. At the same time, government climate policies can do much to change behaviour patterns and encourage markets to mitigate these issues [1]. China, one of the biggest carbon emitters in the world, is facing more pressure internationally. To address the problems associated with climate change, China's National Development and Reform Commission (NDRC) has announced that it will launch carbon emission trading pilots in Beijing, Tianjin, Shanghai, Chongqing, Shenzhen, Guangzhou and Hubei since October 2011. Three years later, the government promulgated the Interim Measures for the Management of Carbon Emissions Trading to further regulate the national carbon market, and gradually linked the pilot carbon markets in 2017 to launch a unified national carbon market.

Launching a unified national carbon market and implementing links to existing pilots means that traders with high marginal abatement costs (MAC) will be able to purchase carbon emission rights from other low-cost domestic trading markets to fulfil their obligations. A unified carbon market can enhance the effectiveness of CO₂ reduction, increase market liquidity, and reduce the risk of carbon leakage caused by the difference in emission reduction intensity between regions, but it will also affect the cost-benefit of traders and the distribution of welfares between provinces [2]. Therefore, it is necessary to make a quantitative analysis of the uncertainty of economic welfare in the link of pilot carbon markets [3].

The difference in emission reduction costs is a prerequisite for the establishment of a carbon trading market. According to the research of existing literature, the basic criterion for evaluating the effectiveness of the carbon trading market is that “the effective market price is equal to the minimum marginal abatement costs” [4]. Scholars have done a lot of research on the cost of emission reduction for a long time and have obtained in abundance. Early on, Nordhaus W.D. [5] made a comprehensive study on it and pointed out that MAC was a standard tool for analysing the impact of environmental policies. According to relevant literature, the earliest Marginal Abatement Cost Curve (MACC) was generated after the impact of two oil crises in the late 1970s [6]. At that time, it was mainly used to study how to reduce oil consumption to reduce energy costs. In the classic literature published by Weitzman, M. L. [7], the author also pointed out that the shape, intercept and slope of MACC are the key factors in deciding whether to use price policy or quantity policy. In the 1990s, Faruqui, A. et al. (1990) [8] applied the MACC to calculate the saving amount of electricity consumption.

Specifically, the MAC of GHGs refers to the cost of each unit of GHG reduction, which effectively describes the functional relationship between reduction and marginal costs [9]. Ellerman, A. D. and A. Decaux (1998) [10] constructed MACC based on the EPA (Emissions Prediction and Policy Analysis) model, obtaining the Marginal Abatement Cost in 12 regions of the world and analysing the advantages of achieving the carbon emission reduction target under the Kyoto protocol based on the market. They found that if carbon trading market links are established among OECD countries, the US, Japan, EU and other OECD countries will receive US \$ 2.3 billion, US \$ 10.49 billion, US \$ 3.3 billion, and US \$ 10 million in trade income respectively. The discovery laid the theoretical foundation for the analysis of carbon trading market links

using MACC. In recent years, the analysis method based on MACC has attracted the attention of environmental economics researchers. For example, a techno-economic policy evaluation of SO₂ abatement options has been conducted by building a system-wide MACC for India [11]; the relationship between the quantity of pollution abated and the marginal cost of abating each additional unit has been traced out [12]. In their research, the MACC is decomposed by sector, and MACC is used to compare the relative cost-effectiveness of Renewable Electricity/ Energy Efficiency/ Fuel Switching and traditional controls.

As for the MAC model construction, according to the review written by Du et al. [13], there are mainly three types: expert-based method, model-derived method and supply-side/production-based. In the last one, the representation form of MAC is derived by defining the production possibility set, which is generally expressed in the form of distance function. The MAC estimated by the distance function modelling method is also called shadow price. The estimated results can also reflect the recent trend of MAC changes and effectively measure the regional emission reduction potential and the cost savings brought by emission trading [14]. Commonly used distance functions include Shephard distance function and Directional distance function (DDF). The Shephard distance function attempts to adjust the desired output and the undesired output in the same ratio, while the directional distance function allows the desired output to increase while reducing the undesired output. Therefore, compared to the Shephard distance function, the Directional distance function is more in line with the policy decision reality [15]. The distance function methods to estimate MAC can also be divided into parameters and non-parameters, and the latter mainly refers to the estimation using the DEA (Data Envelopment Analysis) while the former generally approximates the distance function with a transcendental logarithm function or a

quadratic function, and then estimates the corresponding parameters through linear programming or random frontier methods [16-17]. Compared with the non-parameters, the parameters method is more flexible, and the estimated function parameters can be used for some subsequent analysis, such as calculating Morishima elasticity of substitution [18].

As China becomes the world's largest CO₂ emitter, there has been a rapidly emerging literature on estimating China's abatement cost of CO₂. Bao-Jun Tang et al. (2020) [19] simulates the MACCs of different sectors in China's ETS and calculate the optimal carbon price of sector coverage scenarios based on the criteria that involve eight sectors in turn. D.J. Ji and P. Zhou (2020) [20] utilize a multi-pollutant parametric output DDF approach, to estimate the MACs of CO₂, SO₂, and NO_x emissions for 105 Chinese cities in 2006–2014. Ke Wang et al. (2017) [21] uses output quadratic DDF and investigates the impact of using different directional vectors representing different carbon mitigation strategies of China's major iron and steel enterprises, they pointed out that the mean CO₂ shadow price of China's iron and steel enterprises is very sensitive to the choice of direction vectors. Li Tao et al. (2010), Cui Lianbiao et al. (2013) and Xia Yan et al. (2012) [22-24] respectively used different functional models to fit the curve, such as classic logarithmic function, exponential function and quadratic function. Due to the short period of trading, it is conceivable that there is a lack of research on economic welfare in China. Fu Jingyan et al. (2015) [25], first proposed the uncertainty of the welfare and the necessity of quantifying the welfare impact of the carbon trading market. However, the study did not take into account the different allowance allocation and different emission reduction targets.

Presently, there are abundant literature on the mature EU carbon market, while there are few researches on China's carbon trading market and its welfare. The

innovations of this paper are as follows: firstly, on the basis of shadow price theory and directional distance function, this paper will build an input-output model containing undesired output to estimate the MAC of 30 provinces (except Hong Kong, Tibet, Macau and Taiwan due to the missing data) by using the parametric method. Different from previous studies, this paper fits the MACCs of the representative cities and provinces in China in detail, instead of just dividing each province into several categories for analysis, and expands the trading subjects of carbon trading market from regions to provinces. Secondly, in the empirical part, this paper quantifies the welfare of establishing a unified carbon trading market, simulate the welfare changes of provincial carbon trading markets under different allowance allocation and different reduction targets. A quantitative analysis of the welfare of the unified Chinese carbon trading market can provide a reference for enterprises and provinces participating in the carbon market. It can also help policy makers to regulate the carbon market and provide an evidence for ETS.

Methods

Directional distance function

MAC measures the tradeoff between desirable and undesirable outputs, or simply, the value of desirable output that would be foregone to reduce undesirable output by a unit. In the existing literature, MAC is normally referred to as the shadow price or marginal rate of transformation between desirable output and undesirable output [26-30]. The production possible set is as follows:

$$P(x) = \{(y, b): x \text{ can produce } (y, b)\} \quad (1)$$

x represents the input vector, y denotes the desired output vector, and b represents the undesired output vector.

In addition to the traditional neoclassical assumptions, such as compactness and free disposability of inputs and desirable outputs, the technology typically imposes two crucial assumptions on the output set, i.e. the null-jointness assumption and the weak disposability assumption. The null-jointness assumption says that desirable outputs are jointly produced with undesirable outputs. Formally, it assumes that if $(y, b) \in P(x)$ and $b = 0$, then $y = 0$, which implies that desirable output cannot be produced if no undesirable output is produced. The weak disposability assumption postulates that any proportional reduction of desirable and undesirable outputs is feasible. Formally, it assumes that if $(y, b) \in P(x)$ and $0 \leq \theta \leq 1$, then $(\theta y, \theta b) \in P(x)$, which implies that it is costly to reduce the undesirable outputs.

The specific economic expression thereof is as follows:

$$P(x) = \{(x, y, b): \sum_{i=1}^n \lambda_i x_i \leq x_n, \sum_{i=1}^n \lambda_i y_i \leq y_n, \sum_{i=1}^n \lambda_i b_i = b, \beta \geq 0, \lambda_i \geq 0\} \quad (2)$$

Where i represents province, n represents different years.

The best situation is that the combination set includes the maximum desired output and the minimum undesired output. Therefore, the series of combinations with maximum desired output and the minimum undesired output constitutes the production frontier curve. The direction distance function value is the maximum distance value from each combination point to the production frontier curve.

Suppose that $g = (g_y, g_b)$ represents the direction vector and $\overrightarrow{D_0}$ represents the direction distance function. The specific expression thereof is as follows:

$$\overrightarrow{D_0}(x, y, b, g_y, g_b) = \max\{\beta: (y + \beta g_y, b - \beta g_b) \in P(x)\} \quad (3)$$

As is shown in Figure 1, point A is a combination of the desired output and the undesired output in the set of $P(x)$; point B is a combination of the production frontier. Tangents are tangential to point B, and AB is perpendicular to the tangent line.

Figure 1. The graph of the directional distance function (drawn by the author)

Following the direction (g_y, g_b) to adjust from A to B, this can maximize the desired output and reduce undesired outputs, finally reaching perfect point B on the production frontier curve. The maximum distance of point A to point B is the ratio of the $\overrightarrow{AB}$ to $\overrightarrow{Og}$. The β value which the direction distance function value at point A is $\overrightarrow{AB}/\overrightarrow{Og}$.

Marginal abatement cost model setting

This paper deduces the shadow price of undesired output from the dual relationship between directional distance function and revenue function. Suppose p_y is the price of desired output, p_b is the price of non-desired output, and w is the price vector of input. Then the revenue function can be defined as:

$$\Pi(w, p_y, p_b) = \max\{p_y y - wx - p_b b : (y, b) \in P(x)\} \quad (4)$$

Formula (4) defines the maximum possible return under the condition of a given input x , it is obvious that the contribution of undesired output to profit is negative, that is, to deal with undesired output requires cost.

Because the production unit is always above or within the production frontier, therefore $\overrightarrow{D_0}(x, y, b, g_y, g_b) \geq 0$, that is to say $(y, b) \in P(x)$ and $\overrightarrow{D_0}(x, y, b, g_y, g_b) \geq 0$ are equivalent. The revenue function can be equivalently defined as:

$$\Pi(w, p_y, p_b) = \max\{p_y y - wx - p_b b : \overrightarrow{D_0}(x, y, b, g_y, g_b) \geq 0\} \quad (5)$$

If $(y, b) \in P(x)$, then:

$$(y_k + \beta g_y, b_k - \beta g_b) = \{[y + \overrightarrow{D_0}(x, y, b; g)g_y, b - \overrightarrow{D_0}(x, y, b; g)g_b] \in P(x)\} \quad (6)$$

The above formula shows that if the output vector is feasible, then the output along the direction after eliminating the inefficiencies is also feasible. Therefore, the revenue function can also be written as follows:

$$\Pi(w, p_y, p_b) \geq (p_y y - wx - p_b b) + p_y \overrightarrow{D_0}(x, y, b; g)g_y + p_b \overrightarrow{D_0}(x, y, b; g)g_b \quad (7)$$

The left side of the inequality in formula (7) is the maximum possible profit, and the right side is the actual profit $(p_y y - wx - p_b b)$ plus the additional benefit after eliminating technical inefficiencies. The additional benefit includes two parts, one is brought by the increasing desired output, that is, $p_y \overrightarrow{D_0}(x, y, b; g)g_y$. The other is brought by the reduction of undesirable output. In essence, due to the decrease in undesired output, the cost of the undesired output deducted from the total benefit also decreases, that is, $p_b \overrightarrow{D_0}(x, y, b; g)g_b$. If the production unit moves along the direction vector to the frontier of the production set $P(x)$, the allocation of output will be efficient, and the inequation will become an equation:

$$\overrightarrow{D_0}(x, y, b; g) \leq \frac{\Pi(w, p_y, p_b) - (p_y y - wx - p_b b)}{p g_y + q g_b} \quad (8)$$

Therefore, the directional output distance function can be defined as:

$$\overrightarrow{D_0}(x, y, b; g) = \min_{py} \left\{ \frac{\Pi(w, p_y, p_b) - (p_y y - wx - p_b b)}{p g_y + q g_b} \right\} \quad (9)$$

Applying the envelope theorem to the formula (9), the shadow price model can be obtained:

$$\frac{\partial \overrightarrow{D_0}(x,y,b;g)}{\partial y} = \frac{-p_y}{p_y g_y + p_b g_b} \leq 0 \quad (10)$$

$$\frac{\partial \overrightarrow{D_0}(x,y,b;g)}{\partial b} = \frac{b}{p_y g_y + p_b g_b} \geq 0 \quad (11)$$

If the price of the desired output (p_y) is known, the price of the undesired output (p_b) can be obtained by the following formula:

$$p_b = -p_y \left(\frac{\frac{\partial \overrightarrow{D_0}(x,y,b;g)}{\partial b}}{\frac{\partial \overrightarrow{D_0}(x,y,b;g)}{\partial y}} \right) \quad (12)$$

Because of the differential property, the parametric distance function can be used to deduce the shadow price, which mainly include transcendental logarithm function and quadratic function. The parameterization of Shephard distance function generally adopts the prior. In this paper, based on the research of Färe et al. [16], the transcendental logarithmic Directional distance function of estimated shadow price is set as follows:

$$\begin{aligned} \ln[1 + \overrightarrow{D_0}(x^{i,t}, y^{i,t}, b^{i,t})] = & \alpha_0 + \sum_{n=1}^3 \beta_n \ln x_n^{i,t} + \\ & \frac{1}{2} \sum_{n=1}^3 \sum_{n'=1}^3 \beta_{nn'} (\ln x_n^{i,t}) (\ln x_{n'}^{i,t}) + \gamma_0 \ln y^{i,t} + \frac{1}{2} \gamma_{00} (\ln x_n^{i,t}) (\ln x_n^{i,t}) + \\ & \frac{1}{2} \varepsilon_1 \ln y^{i,t} \ln b^{i,t} + \delta_0 \ln b^{i,t} + \frac{1}{2} \delta_{00} (\ln b^{i,t}) (\ln b^{i,t}) + \frac{1}{2} \varepsilon_2 \ln b^{i,t} \ln y^{i,t} + \\ & \sum_{n=1}^3 \eta_n \ln x_n^{i,t} \ln y^{i,t} + \sum_{n=1}^3 \mu_n \ln x_n^{i,t} \ln b^{i,t} + v_t t + \frac{1}{2} v_u t^2 + \sum_{n=1}^3 \beta_{nt} \ln t x_n^{i,t} + \\ & \omega_{yt} \ln t y^{i,t} + \omega_{bt} \ln t b^{i,t} \end{aligned} \quad (13)$$

In formula (13), y represents desired output (total value of out-put), b represents undesired output (CO₂ emissions), $n, n' = 1, 2, 3$ represent three input vectors x (capital stock, labor, and energy consumption), $i = 1, 2, \dots, 30$ represent the 30 provinces of China studied in this article. At the same time, the time variable t is added to the equation to consider the time trend, $t = 1, 2, \dots, 9$ corresponds to each year in the span of the study.

To calculate the shadow price, firstly need to estimate the coefficient in formula (13). Formula on the left is $\ln[1 + \overrightarrow{D_0}(x^{i,t}, y^{i,t}, b^{i,t})]$ rather than $\ln \overrightarrow{D_0}(x^{i,t}, y^{i,t}, b^{i,t})$, the reason is that to ensure the logarithmic function is positive. Because in the technological frontier, the value of $\overrightarrow{D_0}(x^i, y^i, b^i)$ is 0. Färe et al. [31] proposed that these coefficients can be estimated by minimizing the deviation between all decision units and the effective frontier. The optimization is expressed as follows:

$$\begin{aligned}
& \max \sum_{t=1}^T \sum_{i=1}^T \ln \overrightarrow{D_0}(x^{i,t}, y^{i,t}, b^{i,t}) \\
& \text{s.t. } \ln \overrightarrow{D_0}(x^{i,t}, y^{i,t}, b^{i,t}) \leq 0 \\
& \quad \frac{\partial \overrightarrow{D_0}(x^{i,t}, y^{i,t}, b^{i,t})}{\partial \ln y^{i,t}} \geq 0 \\
& \quad \frac{\partial \overrightarrow{D_0}(x^{i,t}, y^{i,t}, b^{i,t})}{\partial \ln b^{i,t}} \leq 0 \\
& \quad \frac{\partial \overrightarrow{D_0}(x^{i,t}, y^{i,t}, b^{i,t})}{\partial \ln x_n^{i,t}} \leq 0 \\
& \quad \gamma_0 + \delta_0 = 1 \\
& \quad \gamma_{00} + \delta_1 = 0 \\
& \quad \gamma_{00} + \delta_2 = 0 \\
& \quad \eta_n + \mu_n = 0 \quad n = 1, 2, 3 \\
& \quad \omega_{yt} + \omega_{bt} = 0 \\
& \quad \varepsilon_1 = \varepsilon_2
\end{aligned} \tag{14}$$

The linear programming aims to make effective coefficient estimation for each subject of emission reduction. s.t.1 ensures that all decision-making units shall not exceed the technological frontier; s.t.2-3 defines the price of desired and undesired output as non-negative and non-positive; s.t.4-7 make a first-order homogeneous assumption of output variables, which means that with a given input and technology, the

value of the distance function expands in the same proportion as a certain proportion of output increases. This illustrates the weak disposition of output variables. s.t.8 means that the transcendental logarithm function is given symmetry.

And:

$$\frac{\partial \overrightarrow{D_0}(x,y,b;g)}{\partial b} = \frac{\partial \overrightarrow{D_0}(x,y,b;g)}{\partial \ln[1+\overrightarrow{D_0}(x,y,b;g)]} \times \frac{\partial \ln[1+\overrightarrow{D_0}(x,y,b;g)]}{\partial \ln b} \times \frac{\partial \ln b}{\partial b} = \frac{\partial \ln[1+\overrightarrow{D_0}(x,y,b;g)]}{\partial \ln b} \times \frac{1}{b} \quad (15)$$

$$\frac{\partial \overrightarrow{D_0}(x,y,b;g)}{\partial y} = \frac{\partial \overrightarrow{D_0}(x,y,b;g)}{\partial \ln[1+\overrightarrow{D_0}(x,y,b;g)]} \times \frac{\partial \ln[1+\overrightarrow{D_0}(x,y,b;g)]}{\partial \ln y} \times \frac{\partial \ln y}{\partial y} = \frac{\partial \ln[1+\overrightarrow{D_0}(x,y,b;g)]}{\partial \ln y} \times \frac{1}{y} \quad (16)$$

So:

$$p_b = -p_y \left(\frac{\frac{\partial \ln[1+\overrightarrow{D_0}(x,y,b;g)]}{\partial \ln b}}{\frac{\partial \ln[1+\overrightarrow{D_0}(x,y,b;g)]}{\partial \ln y}} \right) \times \frac{y}{b} \quad (17)$$

$$\frac{\partial \ln[1+\overrightarrow{D_0}(x,y,b;g)]}{\partial \ln b} = \delta_0 + \delta_{00} \ln b^i + \varepsilon \ln y^i + \sum_{n=1}^3 \mu_n \ln x_n^i \quad (18)$$

$$\frac{\partial \ln[1+\overrightarrow{D_0}(x,y,b;g)]}{\partial \ln y} = \gamma_0 + \gamma_{00} \ln y^i + \varepsilon \ln y^i + \sum_{n=1}^3 \eta_n \ln x_n^i \quad (19)$$

Finally, the calculation formula of MAC is:

$$p_b = \frac{\delta_0 + \delta_{00} \ln b^i + \varepsilon \ln y^i + \sum_{n=1}^3 \mu_n \ln x_n^i}{\gamma_0 + \gamma_{00} \ln y^i + \varepsilon \ln y^i + \sum_{n=1}^3 \eta_n \ln x_n^i} \times \frac{y}{b} \quad (20)$$

Welfare analysis

According to *The Economics of Welfare* (A. C. Pigou, 1920) [32], social welfare is usually expressed by economic surplus, which mainly includes producer surplus, consumer surplus and social surplus. Trade-related theories point out that transactions can reduce costs for both parties and increase social welfare. In the national unified carbon trading market, carbon trading participators can reduce the cost of carbon emission reduction, so as to increase their welfare. Different carbon trading participators have different MACCs. Based on the curve, it is possible to analyze the welfare gains obtained by various trading participators in the linking of carbon markets. This article analyzes each province as an independent transaction participator. Figure 2. shows the

changes in costs and welfares of carbon trading participators after participating in the unified market. Assume that there are two participants in the market, MAC_1 and MAC_2 . The horizontal axis represents the carbon reduction (ER), and the vertical axis represents the MAC.

Before the carbon pilot markets is linked, Q_1 , Q_2 represent the value of ER and P_1 , P_2 is the price of MAC of the two participants (Point A and Point B). The area enclosed by the MACC and the horizontal axis (integration of MAC) represents the total cost of emission reduction required by each participator when reducing emissions individually. When the pilot carbon market is linked, the emission reduction of the two participants will be Q_3 and Q_4 respectively through market purchases and sales. The horizontal and vertical coordinates of point A' and B' correspond to emission reduction and marginal abatement cost respectively. A'' and B'' respectively reflect the MAC when the two participators maintain the initial emission reduction. With the formation of a unified carbon market, participants can trade with each other. Under the guidance of market prices, they will choose their own supply and demand, thus reducing the total cost of reduction and increasing the social welfare.

Figure 2. Marginal Cost Curve (Drawn by the author)

When the unified carbon price in the market is lower than the MAC of the individual transaction participant, the participant will choose to purchase carbon quota

in the carbon market to complete the emission reduction target. The demand part is called the “transfer-in”; on the contrary, when the unified carbon price in the market is higher than the MAC of the individual transaction participant, the participant will choose to increase the amount of ER. Meanwhile, the extra quota will be sold in the market and obtain economic benefits from it. the selling part is called the “transfer-out” in this paper. In the carbon trading market, the total market demand and total supply under different prices can be obtained by summing up the transfer-in and transfer-out of all carbon transaction participants. When the market supply and demand are equal, the equilibrium carbon price will be determined. After that, each participant can determine the amount of transfer-in and transfer-out by comparing MAC to equilibrium price, therefore, it can get a new ER after trading. Further, it can be calculated that the cost and welfare changes brought by the unified carbon market to the participants.

Table 1. illustrates the changes in costs and welfares of participants before and after the formation of a unified carbon trading market. The equilibrium price P^* is determined by the total supply and demand of the carbon market; $S(AA'A'')$ and $S(BB'B'')$ represents the income after participating in the carbon markets linking. Before the linking of the carbon pilot markets, $S(OQ_1A)$ and $S(OQ_2B)$ represent the total cost of emission reduction of 1 and 2, whose integrations are calculated as:

$$TC_i = \int_0^{Q_i} MAC_i dER \quad (21)$$

Where $i = 1, 2$ means two participants. After the linking, the carbon emission reduction of $Q_1 + Q_2$ needs to be jointly completed in the unified carbon trading market. As the trade income of $S(AA'A'')$ and $S(BB'B'')$ are obtained by the transfer-in and transfer-out, the net costs of the two participants are $S(OA'A''Q_1)$ and $S(OQ_2B) - S(BB'B'')$ respectively.

Table 1. Welfare Analysis Before and After the Formation of the Unified Market

	Before Linking		After Linking	
	Region 1	Region 2	Region 1	Region 2
ER	Q_1	Q_2	Q_1+Q_2	
MAC	P_1	P_2	P^*	
Cost	$S(OQ_1A)$	$S(OQ_2B)$	$S(OQ_3A')$	$S(OQ_4B')$
Transfer-in/out	0	0	$A'A''$	$-B'B''$
Trade Income	0	0	$S(AA'A'')$	$S(BB'B'')$
Net Cost	$S(OQ_1A)$	$S(OQ_2B)$	$S(OA'A''Q_1)$	$S(OQ_2B)-S(BB'B'')$

Marginal abatement cost model setting Data collection

Data in 30 provinces (except Hong Kong, Tibet, Macau and Taiwan due to the missing data) are taken as research objects, which includes capital stock, labor force, energy consumption, GDP and CO₂ emissions in 2011-2017. The data are collected from China Statistical Yearbook, The National Bureau of Statistics and The China Energy Statistical Yearbook. According to the historical data, we shall predict the variable data for 2020 by regression model. The specific variables are as follows:

(1) Capital stock: we select the perpetual inventory method to calculate the capital stock of each province in China.

$$K_{it} = K_{it-1}(1 - \delta) + I_{it} \quad (22)$$

Where, K_{it} represents the total capital stock this year, K_{it-1} represents the total capital stock of the previous year, and I_{it} represents the total fixed capital formation this year. Based on the 2000-year period, we calculate the capital stock of each of China's provinces from 2011 to 2017. All formulae considered the elimination of price factor.

(2) Labor force: we use the number of people in employment in each province at the end of each year. The sum of the number of employed people from three major industries is selected to represent labor input.

(3) Energy consumption: The data are from the *China Energy Statistical Yearbook* [33].

(4) Desired output: GDP, here we eliminate the effect of price changes into the 2000-year unchanged price.

(5) Undesired output: CO₂ emissions. China has not released CO₂ emissions over the years, and CO₂ emissions mainly come from fossil energy consumption and its transformation. Therefore, this paper adopts the carbon emission calculation method published by IPCC guidelines (2006) to calculate CO₂ emissions in various provinces in China [34]. Calculation should include as many fossil fuels and greenhouse gases as possible from multiple sectors to prevent carbon leaks [35]. We estimate CO₂ emissions by energy types based on the mass balance of carbon.

$$CE_i = AD_i \times EF_i \quad (23)$$

Where CE_i are CO₂ emissions from different energy types, AD_i (activity data) are the fossil fuels combusted within the province boundary measured in physical units (metric tonnes of fuel expressed as t fuel), and EF_i are the emission factors for the relevant fossil fuels. By summarizing the emissions from different energy types together, we obtain the total CO₂ emissions for one province in formula (24).

$$CE = \sum CE_i \quad (24)$$

According to the IPCC guidelines, the CO₂ emissions are calculated based on the fossil fuels' sectoral combustion; see formula (25) below.

$$CE_{ij} = AD_{ij} \times NCV_i \times CC_i \times O_{ij} \quad (25)$$

where CE_{ij} refers to the CO₂ emissions from fossil fuel i burned in sector j ; AD_{ij} represents the fossil fuel consumption by the corresponding fossil fuel types and sectors; NCV_i refers to the net caloric value, which is the heat value produced per physical unit of fossil fuel combustion; CC_i (carbon content) is the CO₂ emissions per net caloric value produced by fossil fuel i ; and O_{ij} is the oxygenation efficiency, which refers to the oxidation ratio during fossil fuel combustion. The subscripts i (fossil fuel) and j (sector) correspond to those used in Appendix A and Appendix B. There are 26 fossil fuels in China's energy statistics systems, listed in the most recent energy balance

table in the China Energy Statistical Yearbook. We merged these fuels into 17 types due to the small consumption and similar quality of certain fuels to that of others, as shown in Table 2. Among the 17 fossil fuels, raw coal, crude oil, and natural gas are primary energy sources. The remaining 14 fuels are classified as secondary energy sources, which are extracted or processed from primary sources. The 47 sectors used in the energy statistical system are also consistent with those used in China's national economic accounting [36] (see Appendix A). Due to all the administrative boundaries (at both the national and provincial scales) that span both urban and rural geographies in China, urban and rural households are listed separately in the multi-scale CO₂ emission inventories [37].

MATLABTM is used to construct the emission inventories with sectoral fossil fuel consumption and emission factors, so as to measure the total carbon emission.

Results & Discussion

Results of DDF value

On the basic model of linear programming, the Directional distance function value of 30 provinces from 2011 to 2017 was calculated by using MATLABTM software in Table 2. The Directional distance function value represents the maximum distance from each combination to the production frontier curve. Here, it refers to the distance from the carbon emission reduction efficiency level of each region to the production frontier curve. As can be seen from Table 2, there is a negative correlation between the distance value and the carbon emission performance level. A smaller value means closer to the optimal efficiency value and less potential for improvement, and vice versa.

Table 2. Directional distance function values of 30 provinces and cities

Province	2011	2012	2013	2014	2015	2016	2017
Beijing	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Tianjin	0.219	0.209	0.190	0.105	0.048	0.076	0.067
Hebei	0.485	0.532	0.542	0.561	0.618	0.608	0.627

Shanxi	0.713	0.751	0.760	0.789	0.827	0.827	0.836
Inner Mongolia	0.637	0.713	0.732	0.732	0.722	0.713	0.751
Liaoning	0.238	0.352	0.380	0.428	0.475	0.494	0.513
Jilin	0.542	0.532	0.551	0.580	0.627	0.656	0.656
Heilongjiang	0.456	0.428	0.380	0.418	0.342	0.371	0.428
Shanghai	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Jiangsu	0.200	0.209	0.209	0.219	0.285	0.276	0.285
Zhejiang	0.200	0.190	0.190	0.190	0.247	0.219	0.228
Anhui	0.437	0.409	0.409	0.418	0.494	0.456	0.475
Fujian	0.181	0.171	0.162	0.190	0.257	0.238	0.247
Jiangxi	0.371	0.342	0.333	0.333	0.428	0.380	0.399
Shandong	0.285	0.390	0.371	0.390	0.475	0.209	0.409
Henan	0.542	0.513	0.513	0.532	0.589	0.589	0.608
Hubei	0.418	0.399	0.342	0.352	0.418	0.390	0.409
Hunan	0.342	0.314	0.285	0.285	0.352	0.333	0.352
Guangdong	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Guangxi	0.456	0.485	0.504	0.504	0.561	0.570	0.570
Hainan	0.285	0.314	0.323	0.380	0.466	0.456	0.494
Chongqing	0.304	0.266	0.200	0.209	0.276	0.228	0.247
Sichuan	0.276	0.247	0.238	0.238	0.266	0.247	0.266
Guizhou	0.722	0.713	0.703	0.713	0.760	0.722	0.722
Yunnan	0.561	0.542	0.532	0.532	0.561	0.561	0.590
Shaanxi	0.931	0.931	0.931	0.361	0.703	0.703	0.713
Gansu	0.561	0.580	0.589	0.608	0.627	0.589	0.608
Qinghai	0.684	0.675	0.694	0.694	0.703	0.703	0.713
Ningxia	0.865	0.865	0.884	0.884	0.893	0.893	0.893
Xinjiang	0.893	0.903	0.912	0.912	0.798	0.779	0.779

Based on the horizontal comparative analysis of the values in Table 2, the areas with high levels of carbon emissions performance such as Beijing, Shanghai, and Guangdong usually present the characteristics of higher economic development, high production efficiency and service-oriented industries; DDF value is equal to or close to zero, indicating that these regions have reached the production frontier and the carbon reduction potential is smaller. In regions with poorer carbon emissions performances such as Shaanxi, Shanxi, and Guizhou, where the economy is less well-developed and reliant on heavier resource-based industries, the DDF value is much greater than zero, indicating that there is huge potential for improvement in these areas. Carbon reduction can be implemented by improving efficiency and changing the industrial structure.

Comparison of MAC between 2011 and 2017

The marginal abatement cost discussed here measures the economic income loss due to the reduction of CO₂, so it should be negative. However, to facilitate comparative analysis, we list the absolute value in Table 3.

Table 3. Marginal abatement costs for 30 provinces and cities in 2011-2017 (CNY/ton)

Province	2011	2012	2013	2014	2015	2016	2017
Beijing	6836	7609	8405	9073	9904	9919	9740
Tianjin	2744	3155	3634	5338	6582	5823	6582
Hebei	556	523	548	581	520	538	523
Shanxi	211	196	196	182	165	165	161
Inner Mongolia	199	154	157	165	185	195	166
Liaoning	1556	1276	1341	1258	1169	1107	1086
Jilin	670	780	836	817	784	702	727
Heilongjiang	985	1110	3354	1357	1751	1632	1460
Shanghai	6510	7275	7642	9133	9666	9683	10097
Jiangsu	2717	2885	3116	3375	3081	3152	3216
Zhejiang	3217	3659	3982	4376	4139	4415	4507
Anhui	1007	1190	1226	1281	1131	1257	1237
Fujian	3542	4100	4845	4581	4519	4723	4810
Jiangxi	1588	1909	2024	2173	1802	2035	2018
Shandong	1481	1210	1451	1416	1159	2222	1444
Henan	660	866	961	985	893	894	871
Hubei	1119	1312	2020	2178	2029	2181	2163
Hunan	1682	2076	2574	2908	2588	2707	2682
Guangdong	7120	16502	9424	10474	13445	13472	14086
Guangxi	1240	1188	1235	1383	1351	1309	1355
Hainan	2313	1321	2472	2146	1680	1735	1501
Chongqing	1946	2474	3863	3942	3782	4229	4215
Sichuan	2408	2771	3073	3343	3755	3915	3903
Guizhou	159	176	196	217	190	234	243
Yunnan	595	687	802	975	1093	1097	1187
Shaanxi	23	23	23	866	315	315	325
Gansu	447	458	482	487	505	582	571
Qinghai	359	348	320	383	460	460	447
Ningxia	124	127	122	123	121	121	120
Xinjiang	141	133	124	124	210	222	223

We first measure the overall level of abatement costs across the country. The average cost of CO₂ MAC in 30 provinces during 2011-2017 was 2567 CNY / ton, of which the minimum value was 20 CNY / ton and the maximum value was 19186 CNY / ton. The gap was quite large. Results show that there are great differences in the

emission abatement cost among 30 provinces and cities. It can be seen that the overall abatement cost of the country from 2011 to 2017 is increasing. The regions with high carbon emission abatement costs are mainly concentrated in a few provinces and cities. This distribution creates conditions for carbon trading. Carbon trading has been recognized because of its incomparable advantages in terms of emission reduction costs, emission reduction effects, and political feasibility [38]. The heterogeneity of regional emission abatement costs provides the possibility for the formation of carbon market. Provinces with higher abatement costs can reduce their costs by purchasing carbon quotas from other provinces. Provinces with lower carbon emission abatement costs can earn additional economic benefits (welfares) by selling. Figure 3 is the average ranking chart of the MAC of each province from 2011 to 2017.

Figure 3. Average Ranking of the MAC from 2011 to 2017 (CNY/ton)

Obviously, the cost in Guangdong is significantly higher than that in other regions (with an average value of 12075 CNY /ton), followed by Beijing (with an average value of 8784 CNY /ton), Shanghai (with an average value of 8572 CNY /ton), Tianjin (with an average value of 4837 CNY /ton) and Fujian (with an average value of 4446 CNY /ton). The authors analysed the reason why there is a big gap between Guangdong and

and other provinces. As the best-developed carbon pilot in China, Guangdong takes the lead in green innovation development. Data from Guangzhou Carbon Emission Exchange shows that by July 2020, the cumulative trading volume in Guangdong had reached 155 million tons, accounting for 38.68% of the national carbon market, ranking first in the country; the cumulative transaction amount was 3.1 billion-yuan, accounting for 34.69% of the national carbon trading pilots, indicating that the emission reduction potential in Guangdong is limited, and reducing carbon emissions by increasing efficiency will incur a significant cost. Reducing the amount of CO₂ emissions per unit GDP will sacrifice more economic revenue than the price per unit carbon dioxide emission rights, therefore, to maximize profits, it is more reasonable to purchase carbon emission rights in the future unified market.

The emission reduction costs in Xinjiang, Ningxia, etc. are the lowest, and emission reduction program can be implemented continuously. The economic revenue that these provinces have sacrificed in reducing their CO₂ emissions is less than the price per unit CO₂ emission rights, therefore, to maximize profits, these provinces may consider trading surplus carbon emission allowances, or even shut down low-efficiency plants to reduce emissions and trade the saved carbon allowances. This will not only achieve the emission reduction targets, but also generate more revenue, and there will be a certain amount of residual income after accounting for the reduction in scale. Summarizing the comparison between individual provinces, the polarization between provinces is obvious, and Pareto improvement¹ can be achieved by undertaking certain reasonable transactions. Without the losses of some provinces, an increase in total revenue can be realized.

¹ Pareto Improvement: If we adjust the allocation of certain resources, some people's situation will be improved, while others' situation will at least remain unchanged. The adjustment that accords with this nature is called Pareto Improvement.

Fitting of the MAC curve of CO₂ emission

After calculating the marginal abatement costs of 30 provinces, we would use functions to fit the MAC curves. Many scholars agree that the MACC shows a single-increasing convex function with the increase of emission reduction [39]. After many tests, this paper decided to use the form of logarithmic function to fit the MACCs, the relevant equations are as follows:

$$MAC(r_i) = \alpha + \beta \ln(1 - r_i) \quad (26)$$

$$r_i = \frac{ER_i}{CE_i} \times 100\% \quad (27)$$

$MAC(r_i)$ represents the CO₂ marginal abatement cost when the emission reduction rate is r_i , α and β are the parameters to be estimated. Obviously, the coefficient β in formula (26) will determine the steepness of the CO₂ MACC, in other words, β represents the difficulty of CO₂ emission reduction in different provinces. Therefore, β must be a negative value, and the greater the absolute value of β is, the faster the CO₂ MAC curve rises. Calculate the β value of all provinces and list the absolute value of β in 30 provinces in Figure 4.

Figure 4. β -Absolute Value in 30 Provinces

The smallest β -absolute value is 0.02, and the largest β -absolute value is 0.833. In

addition, the β -absolute value in more developed provinces are significantly higher, such as Guangdong, Beijing, Shanghai and Jiangsu, while that of less developed provinces in the west is significantly lower than the average level. As the MACC rises faster in eastern region, it will be more difficult for eastern provinces to reduce emissions. Conversely, less developed regions in the west, such as Ningxia, Xinjiang, and Qinghai, will have greater reduction potential than eastern provinces. In other words, under the same CO₂ emission reduction target, the cost in the western region will be much lower than that in the eastern region. Therefore, in the initial stage of ETS, the government can allocate relatively more emission reduction tasks to the western region in order to maximize the overall welfare of the society. But at the same time, western region may be difficult to achieve the task of reducing emissions because of the low output and economic level. Therefore, the government should also give the western region more financial support. As long as the government's financial support is lower than the difference in emission reduction costs caused by more tasks in the western region, there will be a Pareto improvement effect at the level of overall social welfare.

The CO₂ MACCs of representative provinces: Guangdong, Beijing, Ningxia were drawn in this paper (see Figure 5a, 5b, 5c). The upward sloping curve indicates that with the increase of emission reduction rate (r_i), the MAC will gradually increase, and the emission reduction work of all provinces will become more difficult. In the figure, the MACC of Guangdong is obviously steeper than that of Beijing, while Ningxia has the flattest curve due to the smallest β -absolute value.

Figure 5a, 5b, 5c. MACC of Guangdong, Beijing and Ningxia

Welfare measurement in Chinese 30 provinces under two scenarios

Back in 2009, the Chinese government pledged to reduce carbon intensity by 40% to 45% from 2005 levels by 2020. At the end of 2017, China had achieved a 46% reduction in carbon intensity compared with 2005 and achieved its emission reduction target ahead of schedule. Since then, the Chinese government has pledged to reduce carbon intensity by 60% to 65% from 2005 levels by 2030. Based on the actual situation of the Chinese government's emission reduction, this paper takes the 2030 emission reduction target as the research object to compare the emission reduction costs and welfare effects of different provinces under different emission reduction targets.

According to the emission reduction targets set by the country, this paper analyzes the two scenarios separately. Scenario 1 is that the carbon intensity in 2030 is 65% lower than that in 2005; Scenario 2 is that the carbon intensity in 2030 is 60% lower than that in 2005. In Scenario 1, the carbon intensity at the end of 2017 has been reduced by 46% compared with 2005, that is, 241000 CNY /ton. To achieve the target, carbon intensity needs to be reduced by 3% per year on average from 2018 to 2030. In Scenario 2, the carbon intensity would need to be reduced by an average of 2% per year from 2018 to 2030.

On the basis of the carbon intensity, it is easy to get the CO₂ emission limits under different scenarios, and the limitation can be distributed to various provinces in the light of different allowance allocation principles. Allowance allocation can be divided into free distribution and auction. Since China is currently at the initial stage of establishing a carbon trading market, auction allocation will lead to a large fluctuation in the price, which will have a great impact on industries. Therefore, this paper adopts free distribution to allocate limitation to all province. In the process of free distribution, the principle must give consideration to both efficiency and fairness. In accordance with this idea, this paper determines the allowance allocation based on the historical emissions of provinces, which is also adopted by EU ETS at the beginning of the establishment.

Figure 6 depicts the provincial welfare of 30 provinces under Scenario 1. As can be seen from the figure, Ningxia, Inner Mongolia, Shaanxi and Guangdong were able to get the most welfare, totaling 24.52 million- CNY, accounting for 44.6% of the total welfare in China. However, the welfare of Heilongjiang, Hubei, Yunnan and other 10 provinces accounted for less than 1% of the national welfare. Ningxia, which has the largest welfare, is 173 times larger than that of Heilongjiang.

Figure 6. China's provincial welfare under Scenario 1 (Unit: ten thousand CNY)

Figure 7 depicts the provincial welfare of 30 provinces under Scenario 2. As shown in the figure, Ningxia, Inner Mongolia, Guangdong and Shaanxi received the most welfare, totaling 24.24 million-CNY, accounting for 45.7% of the total welfare in China. However, the welfare of Heilongjiang, Yunnan, Hubei and other 10 provinces accounted for less than 1% of the national welfare. The welfare of Ningxia with the largest welfare is 341 times that of Heilongjiang province.

Figure 7. China’s provincial welfare under Scenario 2 (Unit: ten thousand CNY)

Figure 8. Welfare comparison between the two scenarios (Unit: ten thousand CNY)

Different emission reduction targets have great influence on the welfare of provinces. By comparing the welfare of each province under two different emission reduction targets, it can be seen that the intensity of emission reduction in scenario 1 is greater than that in scenario 2, the welfare of Guangdong and Fujian increased significantly with the reduction of emission reduction intensity; that of Shaanxi, Beijing and Hubei is basically the same, while the welfare of the other 25 provinces brought down with the decrease of the reduction of emission intensity. This means that if only the welfares that provinces get from the national carbon trading market are taken into account, the stronger the emission reduction efforts are, the more the provinces will get the welfares. However, correspondingly, the equilibrium emissions of provinces will become less, and the pressure to reduce emissions will become greater, which will have a greater impact on production and economy. The results indicate that after setting the initial emission reduction quota, the government agencies should consider the pressure on the subject of emission reduction and the welfare obtained by the carbon trading market.

On the whole, the welfare of each province decreases as the intensity of emission reduction decreases, that is, the overall welfare of scenario 2 is smaller than that of scenario 1. This means that if the welfare of the national unified carbon market is required, and both strong reduction targets and more provincial welfare are taken into account, the balanced emissions of each province will be less correspondingly, the pressure of emission reduction will be greater. Further, the impact on production and economy will be larger. This indicates that after setting the initial allocation mechanism, the government agencies should consider the pressure on participators and the welfare of ETS in the setting of emission reduction targets.

According to the calculation of the above two groups, Ningxia has the highest welfare and the least MAC, Heilongjiang has the least welfare and MAC is in the middle reaches, and Guangdong has the highest MAC and the welfare is pretty high. Therefore, Guangdong, Ningxia and Heilongjiang are selected as the representative provinces for further detailed analysis. Before participating in carbon trading, the shadow prices of Guangdong, Heilongjiang, and Ningxia were 12050 CNY /ton, 1664 CNY /ton, and 122 CNY /ton, assuming that there are only three participators in the market. The difference in emission reduction costs creates the possibility of trading, and each transaction participant should choose to sell or purchase carbon emission allowances based on their respective emission reduction costs and market prices. When the market equilibrium price is greater than the MAC of a certain province, it is the market supplier; on the contrary, when the market equilibrium price is lower than the MAC of a certain province, it is the demander. At the same time, market equilibrium price can be obtained when market supply and demand are equal. In this paper, different market demand and supply quantity are obtained through the constant change of market price by MATLABTM, and the equilibrium price was calculated.

Table 4. Supply and demand under different carbon prices

Carbon price/ CNY	Supplier	Demander	Supply-demand	Clear or not
$0 \leq P^* \leq 122$	none	all	supply < demand	No
$122 \leq P^* < 1664$	Ningxia	Heilongjiang; Guangdong	supply < demand	No
$1664 \leq P^* < 4612$	Ningxia; Heilongjiang	Guangdong	supply < demand	No
$P^* = 4612$	Ningxia; Heilongjiang	Guangdong	supply = demand	Yes
$4612 < P^* \leq 12050$	Ningxia; Heilongjiang	Guangdong	supply > demand	No
$12050 < P^*$	all	none	supply > demand	No

1. When the market price is lower than 122 CNY, the cost of all participators in the market is higher than the market price, so all of them are demander and there is no supplier in the market, and the market cannot be cleared.

2. When the market price is $122 \leq P^* < 1664$ CNY, the market supplier is Ningxia, the supply volume is at most 18 million tons, and the market demanders are Guangdong and Heilongjiang, the demand volume is at least 19 million tons. Supply in the market is less than demand, the market price cannot reach equilibrium, and the market cannot be cleared.

3. When the market price is 4612 CNY, the market supplier is Ningxia and Heilongjiang, the supply volume is 18 million tons and 1.5 million tons respectively, the market demander is Guangdong, the demand volume is 19.5 million tons. Supply in the market is equal to demand. It happens to be in equilibrium at this price, and the market will reach a state of clearing.

4. When the market price is $4612 < P^* \leq 12050$ CNY, as the price increases, the market supplier is Ningxia and Heilongjiang and the supply volume increases accordingly, more than 19.5 million tons; as the demander, Guangdong, the market demand remains unchanged at 19.5 million tons. At this time, the supply in the market is greater than the demand. Market cannot reach the equilibrium state and cannot be cleared, so the equilibrium price cannot be formed.

5. When the market price is higher than 12050 CNY, with the increase of price at this time, Ningxia, Heilongjiang and Guangdong will all become market suppliers, and

the supply and demand in the market cannot reach equilibrium and the market cannot be cleared. There is no market equilibrium price. The specific supply and demand curves are shown in Figure 9.

Figure 9. The supply and demand curve in carbon market

With further analysis on representative provinces, we can draw the following conclusions: (1) The market supply curve is a straight line that slopes upward and to the right. This is due to the fact that the market supply volume continues to increase as market prices rise, and the market suppliers gradually expanded from the original Ningxia to Heilongjiang. (2) When the market price reaches 4612 CNY, the market supply and demand are equal. From the perspective of cost-welfare relationship: (1) The costs and welfares of different participators in the linking process of carbon trading market are different. Ningxia has the largest welfare, followed by Guangdong and Heilongjiang. At least, it is necessary to pay attention to the possible unfair problems in the distribution of welfare during the establishment of a unified carbon market.

Conclusions

For the first time, this article combines the theoretical model of shadow prices with the analysis of China's carbon trading market in an attempt to analyze the cost and

welfare of Chinese provinces and cities on the unified carbon trading market. This paper adds the time trend factor to the directional distance function, and then further combines the parameter method to estimate the shadow price of CO₂ in 30 provinces in China from 2011 to 2017. Subsequently, shadow prices and emission reduction rates were used to simulate MACC in 30 provinces. Finally, analyze the welfare of all provinces in the carbon trading market. The conclusions drawn in this article mainly include the following:

a. The study found that the shadow prices of various provinces and cities gradually increased with time during the sample period, which means that for all provinces and cities in China, the cost of reducing CO₂ emissions is gradually increasing.

b. Due to the heterogeneity among provinces, the MACC varies greatly among provinces, which indicates that it is necessary to implement a unified carbon trading market in China. Underdeveloped provinces in the west, such as Ningxia, Xinjiang, and Qinghai Province, have scale effects in the process of reducing emissions, so they will have relatively low emission reduction costs and can undertake more emission reduction tasks than the eastern regions.

c. The welfare of various provinces differs greatly under different emission reduction targets. The establishment of a nationwide unified carbon trading market has been postponed repeatedly, largely due to the gaps in emission reduction costs and uneven distribution of welfares among provinces. Government agencies must consider the principles of efficiency and fairness in the process of setting up the allocation mechanism to strive for achieve emission reduction goals while reducing the impact on the economy.

In addition, this article puts forward several policy suggestions in conjunction with the establishment of the unified carbon trading market:

a. From the perspective of the allocation of national emission reduction tasks, the differences among regions should be fully considered and a reasonable allocation should be made. The economic level, emission reduction capacity, and initial quota of each province will greatly affect the welfare on the carbon trading market. Therefore, when setting emission reduction targets for provinces and cities, the government must fully understand the actual situation in each region, take into consideration a series of factors such as economic level, population size, historical emissions, and scale effects to rationally set emission reduction targets [40].

b. Expand the scale of the carbon trading market, include more trading participators and industries, and develop more new carbon trading products. At the current initial stage, the Chinese government has only included the power industry in the national carbon trading market. However, the participation of more regions and industries will allow the emission rights to fully flow in the market and form a more instructive equilibrium price. The government should gradually expand the scope of the industry and the subject of transactions involved in the carbon market.

In addition, the development of carbon trading products can also accelerate market liquidity. At present, there only exists trading products such as carbon emission rights. In the future, carbon options, carbon futures and other financial products can be further developed to increase trading varieties and further use market-oriented mechanisms. To achieve the optimal effect of resource allocation and reduce the cost of emission reduction of the whole society.

c. Vigorously develop and apply various new energy sources to promote technological progress. China's previous economic development was extensive and brought serious environmental pollution, so the task of reducing greenhouse gas emissions is very serious. However, vigorously developing and applying new energy

sources, such as wind energy, solar energy, and nuclear energy, can reduce the dependence of China's economy on fossil energy, thereby effectively reducing greenhouse gas emissions.

Appendix A

Appendix A. Fossil Fuels & Emission Factors (NCV_i,CC_i)

No.(i)Unit	Fuels in China's Energy Statistics	Fuels in this study	NCViPJ/10 ⁴ tonnes, 10 ⁸ m ³	CC _i tonne C/ TJ
1	Raw coal	Raw coal	0.21	26.32
2	Cleaned coal	Cleaned coal	0.26	26.32
3	Other washed coal	Other washed coal	0.15	26.32
4	Briquettes	Briquette	0.18	26.32
	Gangue			
5	Coke	Coke	0.28	31.38
6	Coke oven gas	Coke over gas	1.61	21.49
7	Blast furnace gas	Other gas	0.83	21.49
	Converter gas			
	Other gas			
8	Other coking products	Other coking products	0.28	27.45
9	Crude Oil	Crude oil	0.43	20.08
10	Gasoline	Gasoline	0.44	18.9
11	Kerosene	Kerosene	0.44	19.6
12	Diesel oil	Diesel oil	0.43	20.2
13	Fuel oil	Fuel oil	0.43	21.1
14	Naphtha	Other petroleum products	0.51	17.2
	Lubricants			
	Paraffin			

	White spirit			
	Bitumen asphalt			
	Petroleum coke			
	Other petroleum products			
15	Liquefied petroleum gas	LPG	0.47	20
16	Refinery gas	Refinery gas	0.43	20.2
17	Nature gas	Nature gas	3.89	15.32

Appendix B

o. (j)	Socioeconomic sectors	Category		
	Farming, Forestry, Animal Husbandry, Fishery and Water Conservancy	The primary industry		
	Coal Mining and Dressing	Energy production	Manufacturing industries	
	Petroleum and Natural Gas Extraction	Energy production		
	Ferrous Metals Mining and Dressing	Energy production		

	Nonferrous Metals Mining and Dressing	Energy production	
	Non-metal Minerals Mining and Dressing	Energy production	
	Other Minerals Mining and Dressing	Energy production	
	Logging and Transport of Wood and Bamboo	Light manufacturing	
	Food Processing	Light manufacturing	
0	Food Production	Light manufacturing	
1	Beverage Production	Light manufacturing	
2	Tobacco Processing	Light manufacturing	
3	Textile Industry	Light manufacturing	
4	Garments and Other Fibre Products	Light manufacturing	
5	Leather, Furs, Down and Related Products	Light manufacturing	

6	Timber Processing, Bamboo, Cane, Palm Fibre & Straw Products	Light manufacturing	
7	Furniture Manufacturing	Light manufacturing	
8	Papermaking and Paper Products	Light manufacturing	
9	Printing and Record Medium Reproduction	Light manufacturing	
0	Cultural, Educational and Sports Articles	Light manufacturing	
1	Petroleum Processing and Coking	Energy production	
2	Raw Chemical Materials and Chemical Products	Heavy manufacturing	
3	Medical and Pharmaceutical Products	Light manufacturing	
4	Chemical Fibre	Heavy manufacturing	
5	Rubber Products	Heavy manufacturing	

6	Plastic Products	Heavy manufacturing	
7	Non-metal Mineral Products	Heavy manufacturing	
8	Smelting and Pressing of Ferrous Metals	Heavy manufacturing	
9	Smelting and Pressing of Nonferrous Metals	Heavy manufacturing	
0	Metal Products	Heavy manufacturing	
1	Ordinary Machinery	Heavy manufacturing	
2	Equipment for Special Purposes	Heavy manufacturing	
3	Transportation Equipment manufacturing	Heavy manufacturing	
4	Electric Equipment and Machinery	High-tech industry	
5	Electronic and Telecommunications Equipment	High-tech industry	

6	Instruments, Meters, Cultural and Office Machinery	High-tech industry	
7	Other Manufacturing Industry	High-tech industry	
8	Scrap and waste	High-tech industry	
9	Production and Supply of Electric Power, Steam and Hot Water	Energy production	
0	Production and Supply of Gas	Energy production	
1	Production and Supply of Tap Water	Heavy manufacturing	
2	Construction	Construction	
3	Transportation, Storage, Post and Telecommunication Services	Services sectors	
4	Wholesale, Retail Trade and Catering Services		

5	Other Service Sectors		
6	Urban Resident Energy Usage	Household	
7	Rural Resident Energy Usage		

Declarations

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Lei Su designed the study. Xinru Ji performed the research, analyzed data and wrote the paper. Lei Su commented on the manuscript and contributed to additional analyses and interpretations of results. All authors read and approved the final manuscript.

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