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Study on Feasible Carbon Reduction Paths Based on CO₂ Abatement Cost Curve

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Abstract. Estimation of CO₂ abatement costs is a critical issue in achieving the targets of carbon emission reduction of China while promoting the economic growth. This paper builds an objective programming model to estimate the China's marginal CO₂ abatement costs during 2020-2030. We designed six different mitigation strategies based on China's 60-65 percent carbon intensity reduction target by 2030 and investigated the total economic-wide cost of these strategies. The results show that the non-equal increasing strategies will significantly increase the overall cumulative carbon dioxide emission reduction and reduce the overall cost compared to the non-equal decreasing strategies and equal amount strategies.

1. Introduction

Since China's reform and opening up, energy consumption in China has been growing rapidly, accompanied by the increasing carbon emissions. China's total carbon emissions has reached 9.5 billion tons in 2018, accounting for 29% of the total global emissions. At the same time, China's per capita carbon emissions have also exceeded the global average. As the world's largest CO₂ emitter, China is shouldering the heavy responsibility of reducing emissions in the short term. Under the Paris agreement, China has committed that the emissions of carbon dioxide in China will reach their peak by 2030 or as early as possible and carbon dioxide emissions per unit of GDP will decrease by 60% to 65% from those in 2005. Therefore, it is urgent for China to develop a reasonable and efficient emission reduction system, which can achieve emission reduction targets on the premise of ensuring the steady development of the national economy.

Usually, there is a conflict between CO₂ emission reduction and economic development. How to achieve the emission reduction targets while promoting the economic development has become one of the hot topics in academia in recent years. The purpose of this paper is to estimate the abatement cost and find a cost-effective path of mitigation for 2020-2030.

2. Literature Review

Many scholars have studied the costs of carbon emission based on different methods. There are broadly 3 types of approaches in literature to estimate mitigation costs, which are bottom-up model, top-down model and hybrid model.

The first kind of approach is bottom-up model. Bottom-up models are commonly used for the calculation of detailed emission reduction amount and planning of reduction targets, as well as the



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direct costs of specific mitigation technology and costs of related policies [1-3]. Another kind of model that is often used to estimate abatement costs is top-down model. Different from the bottom-up model that focus on the specific mitigation technology portfolio, the top-down model focus on assessing the potential opportunity costs needed to achieve a specific emission reduction targets. By decomposing the production process, top-down models calculate the implied costs for producers and consumers, which are mainly used for market-oriented reduction policy analysis and evaluation of macroeconomic impacts of measures to reduce emissions caused by macroeconomic aspects. The top-down models can be mainly divided into two types: one is the macroeconomic supply-side model (distance function model), which calculates the shadow price of emission reduction (i.e. opportunity cost) by establishing a set of feasible products that meet technical and economic conditions [4-6]. Another typical top-down model is Computable General Equilibrium (CGE) model, which can integrate economic, energy and environmental module and evaluate the economic impact of different mitigation policies [7].

As the classic top-down model is short of technical details and the traditional bottom-up method lacks analysis of the impact on the macro economy, especially the response to market price fluctuations, some scholars have tried to establish a hybrid model that integrate top-down model and bottom-up model together [8-9].

Among the large literature of estimation of carbon abatement costs, there are some studies focusing on the marginal abatement cost (MAC) of China. Fan et al. [10] has estimated the total cost of achieving the mitigation target under uncertainties for 2016-2020 in passenger car sector. He et al. [11] used a non-parametric DEA approach to estimate the costs savings in different collaboration abatement scenarios. Wu et al. [12] has used non-parametric convergence approach to estimate historical marginal abatement cost of China. Dai et al. [13] made a forward-looking assessment of China's abatement costs over 2016-2020 based on a convex quantile regression.

The model we develop in this paper belongs to top-down models. By employing an optimization model and designing long-term mitigation strategies, we estimate the abatement costs based on 2030 target and assess different mitigation strategies, thus achieving maximum social welfare by reducing costs under the constraints of emission reduction targets.

3. The Model

The marginal abatement cost refers to the change in GDP when reducing additional unit of CO₂ emission, which is used to represent the opportunity cost of achieving CO₂ emission reduction targets. As the abatement cost data is unavailable, shadow price is often used to represent opportunity cost [14-15]. CO₂ shadow price reflects the opportunity costs resulted from reducing per unit of CO₂ emissions. The estimation of shadow prices typically involves three main steps: (1) Construction of linear programming model based on technical progress; (2) Derivation of equation of shadow prices; (3) Calculation of shadow price based on related parameters.

In this paper, we use the MAC objective programming model based on input-output analysis. This model is used to study the dynamic law of abatement cost and predict future marginal abatement curve in China. By constructing a leaner programming model and calculate the shadow price under optimal condition, we can fit the marginal abatement cost curve. Following Xia and Fan [16], we first construct an objective optimization function based on the input-output model, which achieves the given carbon emissions reduction target while maximizes the value added:

$$\text{MAX: } V = \sum_{j=0}^n a_{vj} X_j \quad (j = 1, 2, \dots, 42) \quad (1)$$

where V is the sum of value added of each department divided by input-output analysis, i.e. total GDP. X_j is the total output for department j , a_{vj} is the parameter of value added of department j in the input-output table.

$$a_{vj} = V_j / X_j \quad (2)$$

where V_j is the value added of department j in the input-output table. The constraints of the model include: input-output model constraint; CO₂ emissions constraint; import and export trade constraint.

$$AX + Y + E - I \leq X \quad (3)$$

$$\sum a_{cj} X_j \leq C \quad (4)$$

$$a_{cj} = C_j / X_j \quad (5)$$

$$0 \leq E \leq E^h ; 0 \leq I \leq I^h \quad (6)$$

where A is the direct consumption coefficient matrix in the input-output model, Y is the column vector of the final product in the input-output table, E is the export column vector and I is the import column vector. a_{cj} is the direct carbon emission coefficient of department j in the input-output model, and C represents the total CO₂ emissions. C_j is the carbon emission of department j . E^h is the specified export upper bound vector, and I^h is the specified import upper bound vector. By the above model we can estimate CO₂ shadow price and fit the marginal abatement cost function under GDP optimal scenario:

$$MC = a^{1+R} \quad (7)$$

where MC is the marginal CO₂ emission reduction cost, R is the emission reduction rate, and a is the initial cost of emission reduction. As technological advance is an important factor affecting CO₂, we construct dynamic marginal abatement cost model considering technological progress based on static abatement cost. We propose a Cobb-Douglas production function to describe the relationship between GDP and parameters of technological progress, capital investment and labor input:

$$Y = A(t)L^\alpha K^\beta \mu \quad (8)$$

where Y is total GDP, $A(t)$ is the factor of technical progress, L is the labor input, K is the capital stock, α and β can be interpreted as the output elasticity of labor and capital, respectively. According to the historical value by the National Bureau of Statistics, the output elasticity of labor α is 0.39, and the substitution elasticity of capital β is 0.67. Based on the data of 1990-2018, we estimate the technological progress parameters according to Cobb-Douglas function. We take the logarithm of both sides of the original production function and performs the following regression:

$$\ln A(t) = \ln GDP - \alpha \ln L - \beta \ln K - \ln \mu \quad (9)$$

Then we test the stationarity of the factors of the production function, the results of the test are presented in table 1.

Table 1. The stationarity analysis of variables in production function.

Variable	Testing type (C,T,K)	ADF test statistic	5% level of significance	P-value	Test results
InGDP	(C,0,0)	0.754	-3.04543	0.9899	Nonstationary
Δ InGDP	(C,0,0)	-4.71	-3.04324	0.0018	Stationary
InK	(C,0,0)	0.834	-3.01976	0.9922	Nonstationary
Δ InK	(C,0,0)	-7.228	-3.01987	0.0001	Stationary
InL	(C,0,0)	-2.01	-2.99531	0.2795	Nonstationary
Δ InL	(C,0,0)	-4.677	-3.01544	0.0013	Stationary

Note: Testing type (C,T,K) represent intercept, linear trend and lag lengths respectively.

The results of unit root ADF test indicate that the first-order of natural logarithm of the variable is stationary, so it is possible to construct an autocorrelation function. In this paper we use the vector

autoregressive model (VAR) to fit the technology progress parameters. The VAR model simulated is as follows:

$$A(t) = 0.4253A(t-1) - 0.086A(t-2) + 0.799 + \varepsilon(t) \quad (10)$$

The results show that the reciprocal values of the characteristic roots of technological progress parameters are all within the unit circle, which indicates that the autoregressive model of technological progress parameters is stationary.

Since there is duality in Cobb-Douglas production function and corresponding cost function, the similarity coefficient between the technical progress parameter in the production $A(t)$ and the technical progress parameter in the cost function reaches 0.99. Therefore, we use the technical progress parameter of production function as an alternative to the technical progress parameter in the cost function and obtain the dynamic marginal abatement cost function with technological progress factors:

$$MC = A(t)^{1+R} \quad (11)$$

where $A(t)$ is the initial emission abatement cost based on technological progress parameter, and R indicates that the emission reduction target rate to be reached.

4. Results

In this section, we will present the historical abatement cost and predict abatement cost over 2020-2030. By designing six different mitigation strategies to achieve the target under Paris Agreement, we estimate the total estimation reduction costs under the six different strategies.

4.1. The Statistical Relationship between Chinese CO₂ Emission Growth Rate and GDP Growth Rate

In the baseline scenario, we make a key assumption that no new reduction policies are implemented and the Chinese economy will continue to grow, accompanied by a large amount of CO₂ emissions. By employing a co-integration and error correction model, we establish a measurement model for CO₂ emissions in the baseline scenario where a functional relationship between the GDP growth rate and CO₂ emissions growth rate is constructed. The annual GDP growth rates over the period 1978-2018 come from the China Statistical Yearbook, the annual CO₂ emission growth data from 1978 to 2018 come from World Bank. The relationship between GDP growth rate and CO₂ emission rate is as follows:

$$\Delta y(t) = 0.08853 + 0.1572\Delta x(t) + \mu(t) \quad (12)$$

where $\Delta y(t)$ represents the second-order difference term of CO₂ emission growth rate, $\Delta x(t)$ represents the second-order difference term of GDP growth rate, $\mu(t)$ is the error correction term, which is used to correct the errors of short-term fluctuations deviating from the long-term equilibrium of GDP growth rate and CO₂ emission growth rate. Though this function, we get corresponding CO₂ emission rate in the base scenario. The results are shown in table 2.

Table 2. Relationship between the growth of CO₂ emissions and GDP growth rate.

GDP growth rate	10.0%	9.0%	8.0%	7.5%	7.0%	6.5%	6.0%	5.5%	5.0%
CO ₂ growth rate	17.8%	16.0%	14.2%	13.3%	12.4%	11.5%	10.6%	9.7%	8.8%

As the economy grows in China, the energy demand will also increase. Considering China's heavy reliance on coal, excessive energy consumption will lead to an increase in CO₂ emissions. With the increase of energy efficiency and development of low energy-intensive industries, the rate of change of GDP growth rate and the rate of change of CO₂ emissions will maintain a positive correlation in the long term, but the change of CO₂ emission growth rate will be higher than the change of GDP growth rate.

4.2. Dynamic Evolution of CO₂ Cost Abatement Curve

The major data sources include: (1) The non-competitive input-output tables over 2000-2017 published by National Bureau of Statistics of China. As the formats of input-output tables over the years are not exactly the same, we will adjust all input-output tables in accordance with the format of 2012 input-output table and aggregate the departments into 42, and adjust the values into 2018 standard; (2) Energy consumption data from 1990 to 2018 from China Energy Statistical Yearbook; (3) CO₂ emission factor and parameters of carbon emission calculation formula come from Energy Statistics Yearbook of China and 2006 IPCC Guidelines for National Greenhouse Gas Inventories.

4.2.1 China's Historical Marginal Emission Abatement Costs over the Years. China's historical marginal CO₂ emission abatement costs are presented in figure 1. As figure 1 shows, the marginal abatement cost increase from 232 to 1457 yuan/tCO₂ by reducing the remission from 200 to 1000 million tons in 2018. The marginal abatement cost has also dropped dramatically from 2000 to 2018, mainly due to the continual advances in technology and the wide use of abatement technology. The MAC drops from 3574 yuan/t in 2000 to 1457 yuan/t in 2018 when the CO₂ emission reduction emission reaches 1000 million tons, with a sharp drop of 2117 yuan/t over 18 years.

4.2.2. Prediction of Future Marginal Abatement Cost Curve. According to the dynamic abatement cost function based on technology progress constructed above, we predict the marginal abatement cost of 2020-2030. Figure 2 sheds light on marginal abatement cost curves of 2020-2030. Assuming that the technical progress parameters are not mutated, China's future marginal abatement costs will show a decreasing trend by year for the same amount of emission reduction. For example, the marginal abatement cost drops from 750 yuan/t in 2020 to 582 yuan/t in 2030 when the CO₂ emission reduction emission reaches 500 million tons. Therefore, from the economic perspective, delayed actions to reduce CO₂ emission will lead to lower economy-wide costs.

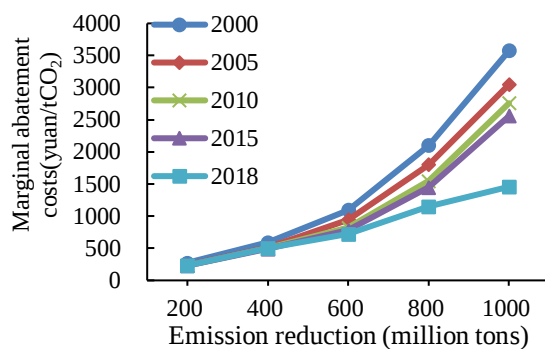


Figure 1. China's historical MAC over 2000-2018.

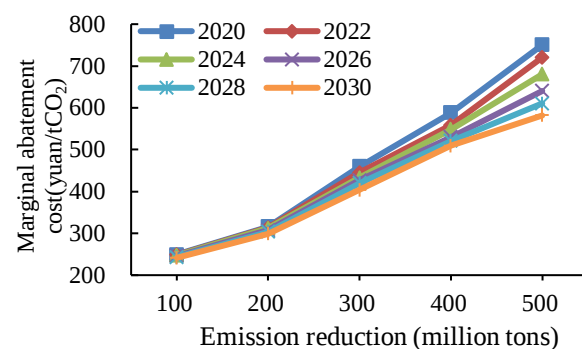


Figure 2. Dynamic MAC over 2020-2030.

4.3. Strategies of China's Future Emission Reduction

When implementing carbon emission reduction targets, an equal amount reduction or a non-equal reduction strategy can be adopted. An equal amount reduction strategy refers to that the targets of carbon intensity reduction are equally distributed to every year, while a non-equal reduction strategy is that carbon emission intensity reduction goal will increase or decrease according to a certain rate of change. In order to explore the optimal reduction strategy, we set 6 different reduction strategies and, including equal and non-equal reduction strategies, shown in table 3.

Based on the marginal cost reduction model, we calculate the cumulative reduction emissions under different strategies and the results are shown in figure 3. The cumulative emission reductions are not the same. Under the non-equal decreasing reduction strategy, the carbon emissions are the

maximum in these three strategies, while non-equal increasing reduction strategy will bring the least emission reduction.

Total abatement costs under six different emission reduction strategies are shown in figure 4. Obviously, achieving the target carbon intensity reduction of 65% from 2005 will cost more than the target of carbon intensity reduction of 60%. We can see that it will incur total costs from 2201 to 2727 billion yuan under the 65% target, from 1200 to 1727 billion yuan under the 60% target. It is found that the abatement cost in the non-equal increasing strategy is less than that in equal strategy either in 60% or 65% of the carbon intensity reduction targets, while the cost of non-equal decreasing strategy is the most. The main reason is that the abatement cost is closely related to the technological progress. As we are experiencing a transition economy and rapid energy structural changes, during which emission reduction technology upgrade rapidly, postponing plans of reducing emissions will lead to lower abatement cost and more potential for reducing emissions. Therefore, by employing the non-equal increasing strategy, we can achieve the promised emission reduction target on the basis of ensuring the minimum macroeconomic losses.

Table 3. Description of six emission reduction strategies.

Abatement target	Strategies	Annual Abatement target
65% reduction of carbon intensity in 2030 compared to 2005 level	Non-equal Increasing	Starting from 2020, each year's emission reduction targets will increase, with an initial target of 0.57%
	Non-equal Decreasing	Starting from 2020, the emission reduction targets will decrease each year, with an initial target of 2.92%
	Equal amount	From 2020, the annual emission reduction target will be the same, with an average annual emission reduction target of 1.75%
60% reduction of carbon intensity in 2030 compared to 2005 level	Non-equal Increasing	Starting from 2020, each year's emission reduction targets will increase, with an initial target of 0.42%
	Non-equal Decreasing	Starting from 2020, the emission reduction targets will decrease each year, with an initial target of 2.16%
	Equal amount	From 2020, the annual emission reduction target will be the same, with an average annual emission reduction target of 1.3%

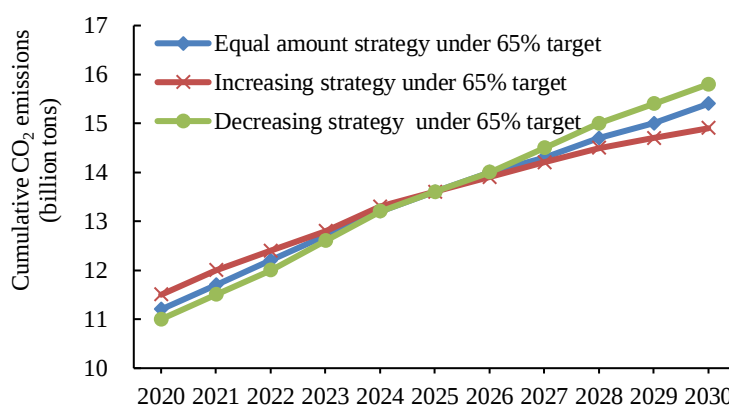


Figure 3. China's future cumulative CO₂ emissions under different emission reduction strategies.

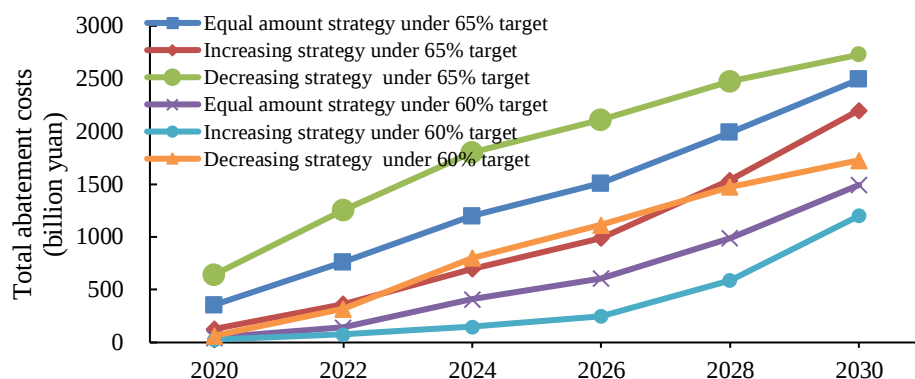


Figure 4. Total abatement costs under different emission reduction strategies.

5. Discussions and Conclusions

Reducing abatement cost has been a major concern to achieve the Chinese emission target. This paper has established the MAC Curves based on technological progress and studied what abatement strategy will induce lower abatement cost while achieving the abatement reduction target by 2030. We estimate the historical abatement cost of and predict abatement cost curve for 2020-2030. The results show that China's marginal abatement costs show a decreasing trend by year for the same amount of emission. Among the 6 mitigation strategies, the non-equal increasing strategies will significantly increase the overall cumulative carbon emission reduction and reduce the overall cost compared to the non-equal decreasing strategies and equal amount strategies when the carbon intensity reduction target being equal. Besides, a more ambitious emission abatement target, i.e. reduction of its emissions intensity by 65% from 2005 in 2030 will induce higher abatement costs than the 60% target.

At this stage, China has taken active actions, including shifting from coal to natural gas, promoting the use of new and renewable energy and encouraging innovation and development of energy-saving technology and so on. Based on the conclusions above, delayed action of carbon emission reduction is a more cost-effective way to achieve the reduction target, which will help to realize a sustainable development and make an active role in reducing global CO₂ emissions and global warming.

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