

“Lock-in” Effect of Emission Standard and Its Impact on the Choice of Market Based Instruments

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Abstract:

A country's existing emission standard policy will lead to “lock in” effect. When the country plans to adopt new market based instruments to control greenhouse gas emissions, it has to take this effect into consideration in choosing among instruments to avoid larger efficiency loss. In this paper, we find that the “lock in” effect will lead to the occurrence of kink point on marginal abatement cost (MAC) curve. This change of shape of MAC curve reminds us to be more cautious in choosing market based instruments when applying Weitzman's rule. We also introduce this concept into the China dynamic multi-regional computable general equilibrium (CGE) model and simulate all regions' MAC curves. After applying Weitzman's rule, we propose the timeline for introducing price instrument under different marginal benefit (MB) curve scenario.

Keywords:

Lock-in Effect, Marginal Abatement Cost Curve, Cap and Trade of Carbon Emissions Rights, Carbon Tax

I. Introduction

In order to tackle climate change and environmental degradation, China has already implemented a few mandatory policies to disentangle its economic growth from fast expansion of greenhouse gas emissions. Intensity regulation has been implemented for the 12th FYP (2011-2015) to reduce the energy-related CO₂ emission for per unit of economic output by 17% from the level of 2010. Another intensity target is the Copenhagen commitment of reducing carbon intensity by 40% -45% in 2020 from that in 2005. One great step ahead the existing intensity targets is the latest official announcement of peaking China's overall GHG emission before 2030. As a fast-growing emerging economy, Chinese government has realized the necessities to optimize the social abatement costs by introducing more market based policy instruments other than traditional command-control policies. However, in this paper we show that the existing intensity standard will cause policy “lock in” effect and this effect will make it different in choosing among market based instruments.

Intuitively, in order to achieve the existing intensity standard, firms in one region must adopt certain clean technologies which causes the “lock in” effect. This “lock in” effect distorts firms’ optimal behavior and leads to the change in shape of marginal abatement cost (MAC) curve. In this paper, we show that a kink point will occur to the MAC curve. According to Weitzman (1974), the relative slope of MAC curve and marginal benefit (MB) curve is the main determinant in choosing between price and quantity instruments under uncertainty. Thus, the kink point of MAC becomes a quite important issue in choosing proper instruments.

II. China’s choice of market based instruments

Among market-based policy instruments, cap and trading and carbon tax are the two most prevailing policies. The former one controls the quantity of total carbon emission and the latter one controls the price of per unit. Given the facts that both of these two policies have pros and cons in various aspects, how to design an appropriate policy regime in contemporary China is to be addressed urgently. There is few domestic experience to learn so far, partly due to the imperfect environmental tax system and also the lack of mature emission trading system. Moreover, there are yet no consensus on the cost-benefit, cost-effectiveness or even well acknowledged impacts efficiency of two different policies from experiences in developed countries. Therefore, price or quantity control is worthy to be validated in China’s low carbon policy regimes.

In theoretical meaning, emission trading and carbon tax are equal to each other in a competitive market with symmetrical information and they can both reach the Pareto optimal result. However, the theoretical prediction is violated by lots of uncertainties arising from market conditions practically. Weitzman (1974) states that choice of quantity and price control measures is dependent on the relative slope of marginal cost curve and marginal benefit curve of emission reduction. Therefore, uncertainties with the supply and demand behavior of emission reduction activities should be considered when choosing controlling price or quantities in pollution mitigation practices. In China’s domestic context, appropriate policy tool with least economic efficiency loss must take above uncertainty factors into consideration for at least three reasons. Firstly, China is in a stage of economic structural transformation, dynamics of industrial upgrading and relocation strengthen the uncertainties of emission abatement activities. Secondly, regional disparities across China are also most prominent sources of uncertainties since these more than 30 provinces have distinct economic

structure, resource endowments and market conditions. Any unified low carbon policy scheme at national level would mean different abatement costs in each province. Last but not the least, the existing command and control policy, i.e. in place mandatory emission intensity target in each region has some lock-in effects with regard to low carbon technology implementation and innovation. Abatement costs paths drive the pattern of costs and benefits of abatement activities in the short and long run. would distort the policy choosing processes. Since all of these factors influence the emission abatement activities in various ways, the characteristics of marginal abatement cost curves should be investigated carefully to develop more appropriate low carbon policies in China.

As pointed out by Weizmann(1974, 1978), if absolute value of the slope of MB curve is less than the absolute value of the slope of MAC curve, price control policies (such as a carbon tax) will be more efficient than quantity control policies (such as cap and trading). Otherwise the quantity control policies will be more efficient. And the difference in efficiency will increase with the increase of difference between the two slopes. However there are few research studies the shape of MAC curve itself when discussing policy selection problems, both under uncertainty and dynamic situation. Therefore, there are great risks to draw policy choice conclusions when applying Weitzman's rule directly. Stranlund and Ben-Haim (2008) extended Weitzman's model to the situation with unstructured uncertainty and find that the same rule proposed by Weitzman still holds. This rule has also been used by many researchers in both simulation and empirical analysis. (Pizer, 1999, 2002; Parry et al., 1999).

Currently, the academia has a consensus that the shape of the MB curve is relatively flat. Kolstad (1996) finds that the each year's newly emitted greenhouse gas emissions contribute very little to global warming and the negative effect of global warming is mainly caused by the total stock of greenhouse gas emissions. In this case, different climate policies will not change the MB curve a lot in a short period.

Several researches have studied the shape of MAC curve. Klepper and Peterson (2006) studied the effects of world energy prices on several major countries' MAC curves. They assume the MAC curve to be global differentiable and their results also show that there are great differences in the slopes of each country's MAC curve. Morris et al.'s (2012) use EPPA model to simulate dynamic MAC curves of several major countries in the world. The results show that both the shape and the

slope of MAC curve may change over time and the MAC curves in their study do not meet the conditions of differentiability.

From these studies of the MAC curve, we can generalize two kinds of findings. Firstly, the shapes of MAC curves differ across countries or regions due to inherent distinctions in many aspects. Regional specific study is definitely needed to support domestic climate policy choice. Besides, because of the dynamic change of MAC curves, the choice of different policies should also change in different period. Secondly, there exists the possibility that the MAC curve is non-differentiable (For example, the MAC curve may contain kink points, jump points, etc) and the properties of the MAC curve need to be further studied.

McKittrick (1999) proposes a new class of MAC curve which may contain kink point. He uses a partial equilibrium model to analyze firm's optimal behavior when there is emission constraint. In his model, firm has two alternative ways to reduce emission, one is to conduct abatement activity and another is to reduce output directly. In the optimal solution, firm will make a tradeoff between the costs of two methods and cause the occurrence of kink point in MAC curve. This result plays quite important role in the selection of climate policies.

In this paper, we extend McKittrick's model and introduce this mechanism into our CGE model to simulate dynamic MAC curves for all regions in China from 2007 to 2020. The article is organized as follows: Section 3 introduces the extension McKittrick model which will be integrated into CGE model; Section 4 describes the framework of dynamic multi-regional general equilibrium model; Section 5 gives the simulation results of regional dynamic MAC curves from 2007 to 2020; Section 6 conducts robust test of the CGE model considering uncertainties; Section 7 reaches the conclusions and policy suggestions.

The main purpose of this paper is to add some numerical proofs for policy choices between carbon tax and trading systems in China. By examining the relationships between regional marginal abatement cost curves and emission reduction targets in the current Chinese policy context, this paper intend to shed some light on the ambiguous policy choosing conditions at more disaggregated regional level.

III. An extended model of the kinked regional MAC Curve

In McKittrick's model, firms own profit maximizing behavior in a complete competitive market and a new variable is added into firms' cost functions to represent emission abatement activity. This micro level analysis can also be applied to industry level analysis if the conditions of Klein-Nataf aggregation problem are satisfied. Klein (1946) stated that if individual firms' first order conditions are satisfied then the aggregate production function must also satisfy same first order conditions. Nataf (1948) showed that such an aggregate production function exists if and only if every firm's production function is additively separable in inputs. So as long as firms have production functions with this separability feature, we can apply the analysis to industry level's aggregate production. For industrial sectors, each sector maximizes its added value of output:

$$\begin{aligned} \max \quad & VA_i(p_i, y_i, \mathbf{w}_i, a_i) = p_i y_i - c_i(\mathbf{w}_i, y_i, a_i) \\ \text{s.t.} \quad & \bar{e}_i = e_i(y_i, a_i) \end{aligned} \quad (1)$$

subscript i represents different regions involved in the emission reduction, while a_i represents the abatement activities these regions take to reduce the emission and it satisfies $a_i \geq 0$. Marginal abatement cost is then defined as the derivative of value-added (VA) with respect to target emission level. In the optimal solution, we can get the marginal abatement cost as:

$$\frac{\partial VA_i}{\partial e_i} = \left(\frac{p_i - c_{iy}}{c_{ia}} - \frac{\partial a_i}{\partial y_i} \right) \frac{dy_i}{de_i} - c_{ia} \frac{\partial a_i}{\partial e_i} \quad (2)$$

Here, abatement activity a_i can be either the investment in new equipment which could reduce the emission or the costs related to developing new energy-saving technologies such as human resources, materials and R&D costs. As is shown in McKittrick's analysis, property of the first derivative of cost function with respect to abatement activity at point $a=0$ decides whether it will occur a kink point of MAC curve. When $c_a(w, y, 0) > 0$, the zero lower bound of abatement activity will not ensure the first part in the bracket on the right side of equation (2) to be always zero, thus changes the shape of MAC curve. The intuition is that when $c_a(w, y, 0) = 0$, it means the initial abatement activity is costless, so the region can choose to adjust the abatement activity freely when it faces certain emission target. However, when $c_a(w, y, 0) > 0$, it means the initial abatement activity is quite costly so that the region can only increase this abatement activity when it faces a rather tight emission target. Then the kink point of MAC curve occurs consequently.

In order to apply this framework in a large scale simulation model, we must first set the form of emission constraint explicitly in equation (1). In reality, the most common policy which link both abatement activity with emission is the emission intensity target in regional level. The emission intensity is defined as one region's total emission level divided by its total output level. If we set the form of emission constraint as $e(y,a)=y/a$, then we can get the relationship among emission, output, abatement activity and intensity target as:

$$\frac{e_i}{y_i} = \frac{1}{a_i} \leq Int_i \quad (3)$$

Int_i is region i 's emission intensity target. From equation (3) we can see that one region's abatement activity input is bounded by this region's emission intensity target. If one region sets a higher policy target which leads to a lower emission intensity, then the minimum abatement activity input level become higher.

The behavior of abatement activity in Equation (3) is also consistent in the general equilibrium setting which means abatement activity increases as absolute emission level decreases. To see this, we take the production function in CES form and the first order conditions give the conditional factor demand function as:

$$e_i^* = ef_i \cdot E_i^* = ef_i \cdot y_i \left[\sum_{j=1}^n \theta_j \left(\frac{p_j}{p_E} \right)^{1-\sigma} \right]^{\frac{\sigma}{1-\sigma}} \quad (4)$$

ef_i is the emission coefficient of energy input E_i in region i . θ_j is the cost share of input j and p_j is the price of input j . σ is the elasticity of substitution of inputs.² Then the change in emission intensity is:

$$d \ln \frac{1}{a_i} = d \ln E_i - d \ln y_i = d \ln \left[\sum_{j=1}^n \theta_j \left(p_j / p_E \right)^{1-\sigma} \right]^{\sigma/(1-\sigma)} \quad (5)$$

Equation (5) shows that the change in intensity fully depends on the changes in relative prices, $d(p_j/p_E)$ and the cost share of different inputs. This means the emission intensity will decrease as long as energy input is substitutable to other inputs and this effect will be magnified if cost share of energy input increases.

² We make a simplified assumption here that there is only one kind of energy input.

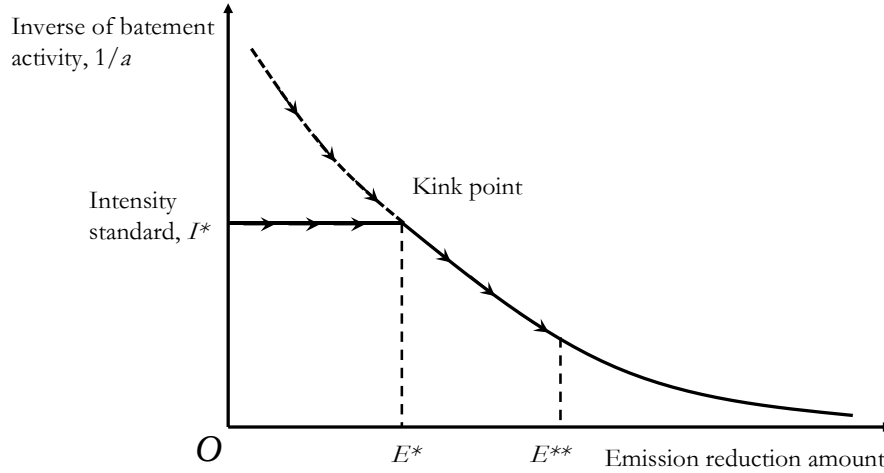


Figure 1 Mechanism of the occurrence of kink point

Figure 1 illustrates the mechanism of the kink point concept in a large scale simulation model. If one region has no intensity target, i.e. a pure null scenario, then the emission reduction efforts allow for unconstrained inputs of abatement activities, which corresponds to a smooth dotted line in the figure. However, if one region initially had an emission intensity standard (e.g. I^*), then the abatement activity would be bounded at certain level greater than zero, as indicated in the solid line in this figure. This level of abatement activity corresponds to an inelastic effort other than output change needed to achieve the intensity target. Once absolute emission E^* was further reduced to a certain level such as E^{**} , then the abatement activity would increase along with the solid line.

From Figure 1, we can see that the position of kink point depends on three elements. First, the intensity target level. Lower intensity level will lead to later occurrence of kink point. Second, the initial emission intensity level. If one region is originally energy intensive, then it will lead to later occurrence of kink point. Third, the increase rate of abatement activity. This factor is a mixed effects affected by one region's relative prices of inputs and cost share of inputs.

IV. The dynamic regional computable general equilibrium model

1. Model Data

This paper builds a recursive dynamic multi-regional CGE model of China. The model uses *The 2007 Regional Input – Output Table* (National Bureau of Statistics of China, 2011) as the baseline to calibrate. It includes 30 regions (all provinces, cities and autonomous regions, except Tibet and Hong Kong, Macao, Taiwan regions). Each region includes 42 production sectors which correspond to the 42 sectors in input-output table, one government and one representative household sector.

Besides, capital and labor are the only two endowment factors used in the model. The model is written in GAMS and uses MPSGE subsystems to get the whole equation system.

Micro-Consistent Matrix

One key problem of using MPSGE subsystem is that we have to first build a dataset called Micro-Consistent Matrix (Rutherford, 1998). We use cross entropy method proposed by Robinson & El-Said (2000) to get the balanced MCM dataset based on *The 2007 Regional Input – Output Table*.

Inter-regional Trade Matrix

Another important problem in building regional CGE model is to build an inter-regional trade matrix dataset. First, we use the gravity model to estimate the raw interregional trade matrix based on regional inflow and outflow data. (Li,) Then cross entropy method is used again to balance the extended MCM which includes the above raw interregional trade matrix. Finally, we get the consistent dataset to build the regional CGE model.

Emission data

In this model, CO₂ emission is calculated from final energy consumption and the emission coefficients are drawn from IPCC Carbon Inventory Accounting Guidelines.

2. Basic Modules

The basic modules of the regional CGE model include production module, demand module, energy/emission module and interregional trade module.

Production

Production module employs nested constant elasticity of substitution (CES) production functions to specify substitution possibilities in production between capital, labor, energy and intermediate inputs. At the top level, intermediate inputs are used in fixed proportions and they are aggregated with energy and a value-added composite of capital and labor.

According to equation (3), we introduce two new endogenous variables into the energy composite production procedure. One represent emission permits used in fixed proportions with different energy inputs, revenue from these emission permits are cycled back to regional household. Another variable is the endogenous emission intensity which is the inverse of abatement activity.

Final consumption demand

Utility function of the representative consumer in each region is given as a constant elasticity of transmission (CET) function which consists of total consumption and net savings:

$$\max_{\{WLF, DINV\}} U_r = \eta \cdot \ln WLF_r + (1 - \eta) \cdot \ln SAV_r \quad (6)$$

WLF_r is region r 's the total residential consumption, SAV_r is region r 's net saving.

Total residential consumption, government consumption and investment demand within each region are all in the form of a combined consumption of a CES energy aggregate and a CES non-energy consumption bundle.

Budget constraint

Household's total income comes from capital income, labor income, government transfer payments and revenue of emission permits. Government's total income comes from tax revenue.

Interregional trade

In the interregional trade module, the model makes the assumption that each region follows small-country behavior within international trade market which means prices of import and export goods are all exogenous. While in domestic market, the each region follows big-country behavior which means each region is no longer a price taker but can affect the domestic price through its interregional trade volume.

For non-energy goods, a three level nested CES demand function is used to specify substitution possibilities among goods from foreign countries, other domestic regions and local market:

$$c_i = \left\{ \alpha_{i1} \left[\alpha_{i2} D_i^{-\varphi} + \alpha_{i3} \left(\left(\sum_i \theta_{ir} INF_{ir}^{-\delta} \right)^{-1/\delta} \right)^{-\varphi} \right]^{\rho} + \alpha_{i4} IMP_i^{-\rho} \right\}^{-1/\rho} \quad (7)$$

c_i represents the total consumption of non-energy good i , subscript r stands for different region. α and θ are share coefficients of different input goods. Besides, φ, ρ and δ are Armington elasticity of substitution among goods from different sources. INF and IMP stands for interregional flow of goods and imports goods respectively.

For energy goods, we assume that energy goods from different countries and regions are homogeneous due to its high degree of standardization, so the energy demand function is a standard

CES function:

$$c_e = \left(\alpha_{e1} DS_e^{-\varepsilon} + \sum_r \theta_{er} INF_{er}^{-\varepsilon} + \alpha_{e4} IMP_e^{-\varepsilon} \right)^{-1/\varepsilon} \quad (8)$$

3. Interregional capital flow module

In this model, we use the putty-clay capital assumption to differentiate capital. This means once free capital is used to form durable goods, it cannot be converted back again. Thus only newly formed capital in each period has the ability to flow across sectors and across regions. Therefore the adjustment of industrial structures and the relocation of industries can only be gradually completed by the depreciation of capital stock and the flow of newly formed free capital. Each region's total investment is determined by the total savings in last period, which is the neoclassic macro-closure condition. Finally, the flow patterns of those newly formed capital are determined by the difference among each region's rate of return of capital. In this model, we use the logit function proposed by Dixon (2012) in MONASH Model to describe the relationship between the rate of return and the growth rate of capital stock:

$$g_{r,i}^k = \frac{\overline{g_{r,i}^k} + \underline{g_{r,i}^k} \cdot e^{cgk(RI_{r,i} - \overline{RI})} \cdot (\overline{g_i^k} - \underline{g_i^k}) / (\overline{g_i^k} - \underline{g_i^k})}{1 + e^{cgk(RI_{r,i} - \overline{RI})} \cdot (\overline{g_i^k} - \underline{g_i^k}) / (\overline{g_i^k} - \underline{g_i^k})} \quad (9)$$

$g_{r,i}^k$ is the expected growth rate of capital stock of sector i in region r . $\overline{g_i^k}$, $\underline{g_i^k}$ and $\overline{g_{r,i}^k}$ stand for the upper bound, lower bound and equilibrium level of capital growth rate of each sector and we take the value as 0.3, 0 and 0.16 respectively. RI stands for the equilibrium value of rate of return on capital which is calculated from the 2007 Input - Output Table. Figure 2 depicts the relation between the expected return of capital (RI^e) and the growth rate of capital accumulation ($g_{r,i}^k$) with the form of logit function.

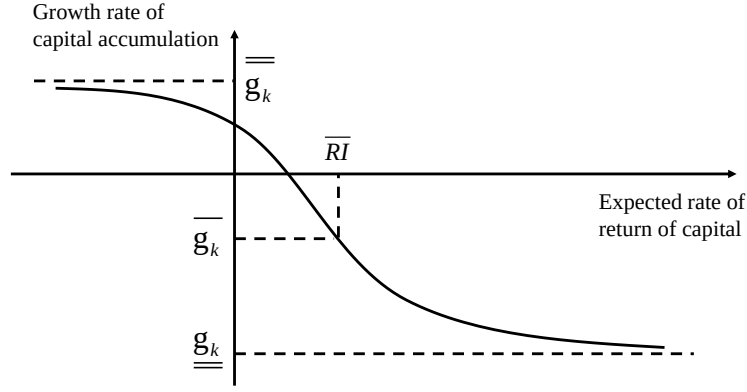


Figure 2 Relationship between capital accumulation and expected rate of return

4. Interregional labor flow module

Another important characteristic of this model is that labors can flow among regions and the amounts of interregional labor flow are determined by each region's total labor supply in the previous period, wage differences among regions and other exogenous parameters. Since value-added data of rural labor and urban labor are not separated in China's input-output table, in this model we assume there is only one kind of labor.

The pattern of labor flow is captured by the extended Lewis model which takes incomplete labor flow into consideration and the labor transfer equation is set as:

$$LM_{d,r}^t = \Theta_{d,r} \cdot \phi_{d,r}^t \cdot \left[\frac{(\mu_{d,r} - c_{d,r}) W_r^{t-1}}{W_d^{t-1}} \right]^\sigma \cdot L_d^{t-1} \quad (10)$$

t represents the year, subscript d and subscript r stands for the local and the targeted region respectively. $LM_{d,r}^t$ stands for the amount of labor transferred from local region to region r in period t and it is in proportion to the total labor force L_d^{t-1} of local region in period $t-1$. W_d and W_r represent the real wage in two regions. $\mu_{d,r}$ stands for the differences in labor quality of two regions and we set $\mu_{d,r}$ equal to one in this model. $c_{d,r}$ represents the cost of labor migration, in form of a certain percentage of the wage level in the targeted region and we assume $c_{d,r}$ equals 0.05. Finally σ stands for the elasticity of labor transfer to capture the incomplete labor flow situation and we assume σ equal 0.8.

In equation (10), $\Theta_{d,r}$ represents the transfer intensity coefficient of the labor flow from this region to the targeted province. It's a constant so that it does not change over time. The coefficient is

calculated by the data from *Tabulation On The 2010 Population Census of People's Republic of China*. $\Phi_{d,r}^t$ is a dummy variable which represents the existence of positive labor flow, that is to say, when there exists labor flow, the variable takes the value one, otherwise takes the value zero.

5. Scenario settings

During year 2005 to 2010, all provinces in China have made great achievements in energy saving and emission reduction according to the requirements of the Eleventh Five-Year Plan. Moreover, the Twelfth Five-Year Plan made further announcement to reduce energy consumption per GDP by 18% and carbon emission per GDP by 17%. In order to implement these targets, the State Council released *the Work Plan for Controlling Greenhouse Gas Emissions for the Twelfth Five-Year Plan period* and put forward clear emission reduction target for all regions during year 2010 to 2015. According to China's commitment at Copenhagen Conference, China will further promote energy saving and emission reduction by 2020 and fulfill the aim to cut the CO₂ emissions per unit of GDP by 40% compared to 2005 level. Follow these climate policies, we set up the business as usual (BAU) scenario of emission intensity targets for all regions in China from 2007 to 2020.

In such kind of BAU scenario, it should be cautious to calculate the marginal abatement cost. In a traditional dynamic recursive model, the dynamic behavior of endowments and parameters follow several rules which are determined exogenously under NULL scenario. Compared to BAU scenario, NULL scenario impose no climate policy restrictions which is obviously not suitable to discuss the effects without take existing abatement effort in previous years into consideration. So one advantage of taking existing policy announcement into consideration is that we can explore the actual cost of policies which reflect the dynamic change in economy.

To realize this BAU scenario setting, we first define two different emission intensity variable, one is endogenous intensity Int_{base}^t and another one is exogenous policy target Int^{t-1}_{BAU} , and $\text{Int}_{base}^t = \text{Int}^{t-1}_{BAU}$. This indicates that emission intensity in year t is upper bounded by the intensity target in year $t-1$.

For CGE model, the whole model equation system can refer to the representation of Abdelkhalek and Dufour (1998).

$$\mathbf{Y} = f(\mathbf{X}, \boldsymbol{\beta}, \gamma) \quad (11)$$

If there are n endogenous variables in the CGE model, then $\mathbf{Y}$ is an endogenous variable vector of

$n \times 1$. $\mathbf{X}$ is an exogenous variable vector (e.g. policy variable). $\boldsymbol{\beta}$ is the free parameter vector, $\boldsymbol{\gamma}$ is the calibrated share parameter vector. Then we can calculate each region's total emission in BAU scenario in year t by:

$$\mathbf{e}_{base,t}^{*,t} = \mathbf{EF} \cdot f(\mathbf{X}, \boldsymbol{\beta}, \boldsymbol{\gamma} | \mathbf{Int}_{base}^t = \mathbf{Int}_{BAU}^{t-1}), \mathbf{Int}_{BAU}^{t-1} \subset \mathbf{X} \quad (12)$$

$\mathbf{e}_{base}^*$ is the $j \times 1$ vector of regional total emission used in equation (1). $\mathbf{EF}$ is the $j \times n$ matrix of emission coefficient of all regions. $\mathbf{Int}$ is the $j \times 1$ vector of emission intensity of all regions. Hence we can get the marginal abatement costs for all regions under the constraint **target**:

$$\mathbf{MAC}_e^t \Leftarrow f(\mathbf{X}, \boldsymbol{\beta}, \boldsymbol{\gamma} | \mathbf{e} \leq (\mathbf{I} - \mathbf{target}) \mathbf{e}_{base}^{*,t}, \mathbf{Int}_{base}^t \leq \mathbf{Int}_{BAU}^t) \quad (13)$$

Here, **target** is a $j \times j$ diagonal matrix represents each region's target emission reduction rate. This reduction rate is set exogenously from 0 to 50 percent step by 1 percent to simulate the MAC curve.

Figure 3 illustrates the dynamic MAC curves in BAU scenario.

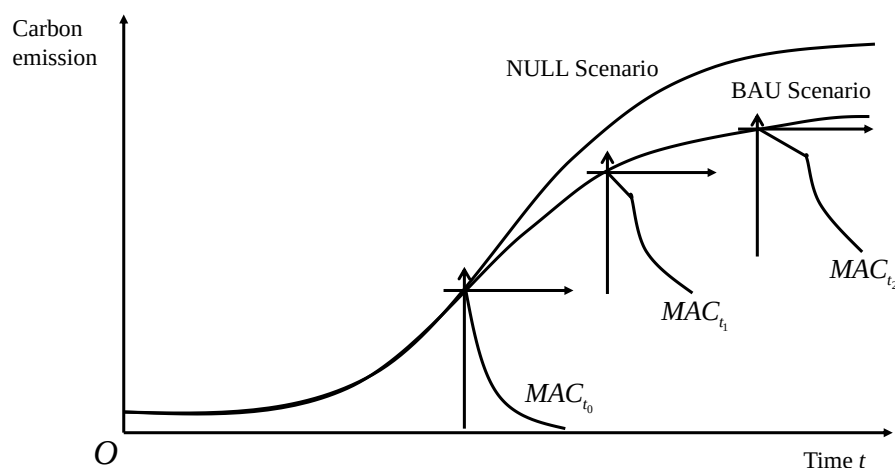


Figure 3 The dynamic MAC curve based on the BAU Scenario

V. Simulation Results and Analyses

1. Shapes of regional MAC curves

Figure 4 presents MAC curve results of two regions, Beijing and Qinghai. The figure is a surface of marginal abatement costs combining two dimensions. One dimension is year from 2007 to 2020 and another dimension is emission reduction rate from zero to 50 percent. All other regions' MAC surface looks similar but with only difference in their absolute level. Confirming basic economic intuition, if one region keep current emission intensity level, then it will have no extra abatement

cost and if emission reduction target becomes tighter, then it will cause higher abatement cost.

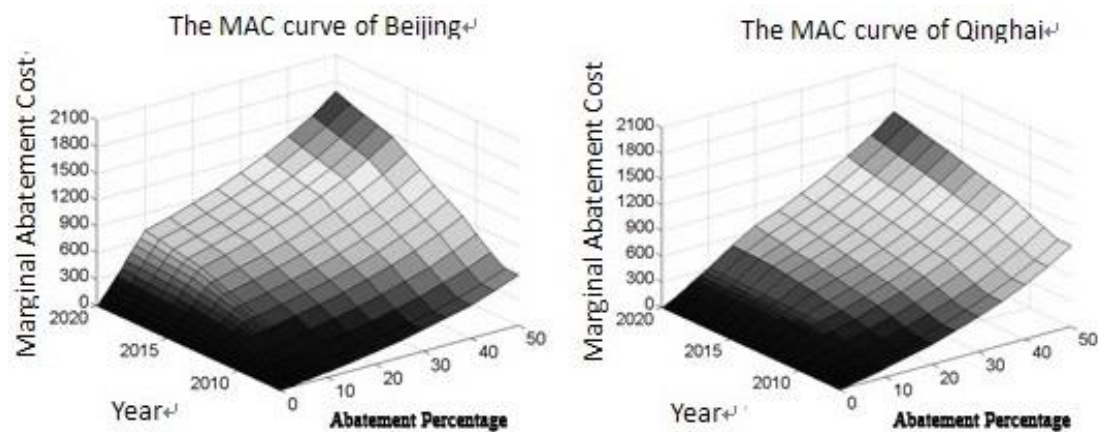


Figure 4 The surface charts of the dynamic MAC curves of Beijing and Qinghai

The MAC curve of Beijing can be seen as a representative curve for the reason that most regions' curves have quite similar shape as of Beijing. However, only Qinghai's MAC curve appears to be quite flat. We can see this result more clearly in Figure 5 if we depict each year's MAC curve individually. The results also confirm the theoretical prediction of the shape of MAC curve that kink points will occur as target goes tighter, no matter the slope of MAC curves.

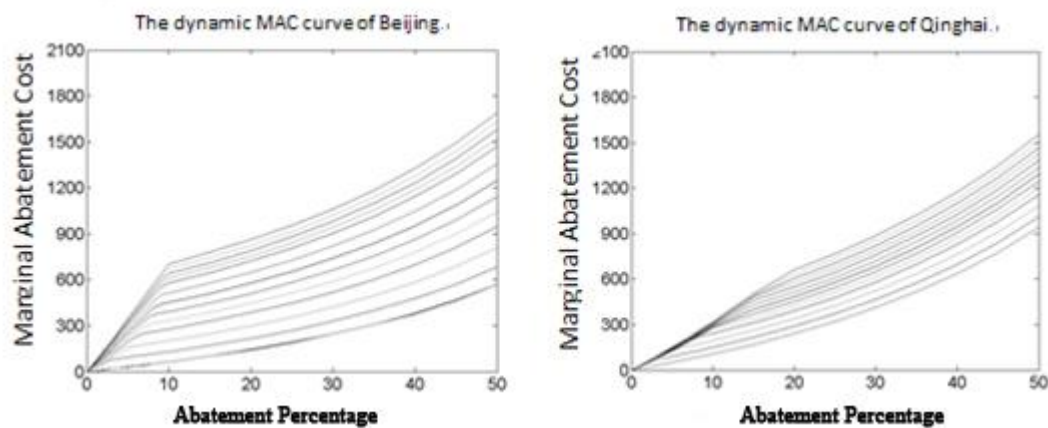


Figure 5 The cross-sectional views of the dynamic MAC curves of Beijing and Qinghai

Note: From bottom to above is the MAC curve under different abatement rates each year from 2007 to 2020

From the results shown in Figure 5, we can draw two preliminary conclusions about regional dynamic MAC curves:

Firstly, the absolute level MAC curve increases over time. It means that if one region faces same reduction target every year, the abatement cost will go up gradually, which is in parallel to our common sense. In the BAU Scenario, the difficulty to reduce same percentage of emission increases

as emission intensity constraint changes monotonically, thus pushing the MAC curve to shift upward. Secondly, kink points occur and they shift rightward over time. As shown in the theoretical model, there are two kinds of ways to reduce emission, reducing output directly and increasing abatement activities. Each region will make a tradeoff between costs of two choices. On one hand, when the cost of reducing output exceeds abatement activity cost, both methods will be taken and thus leading to kink points. On the other hand, when the intensity target goes stricter, it becomes more difficult to reduce emissions. This trend leads to the increase of initial abatement activity cost and gives more potential to reducing output. As a result, the occurrence of kink points is delayed.

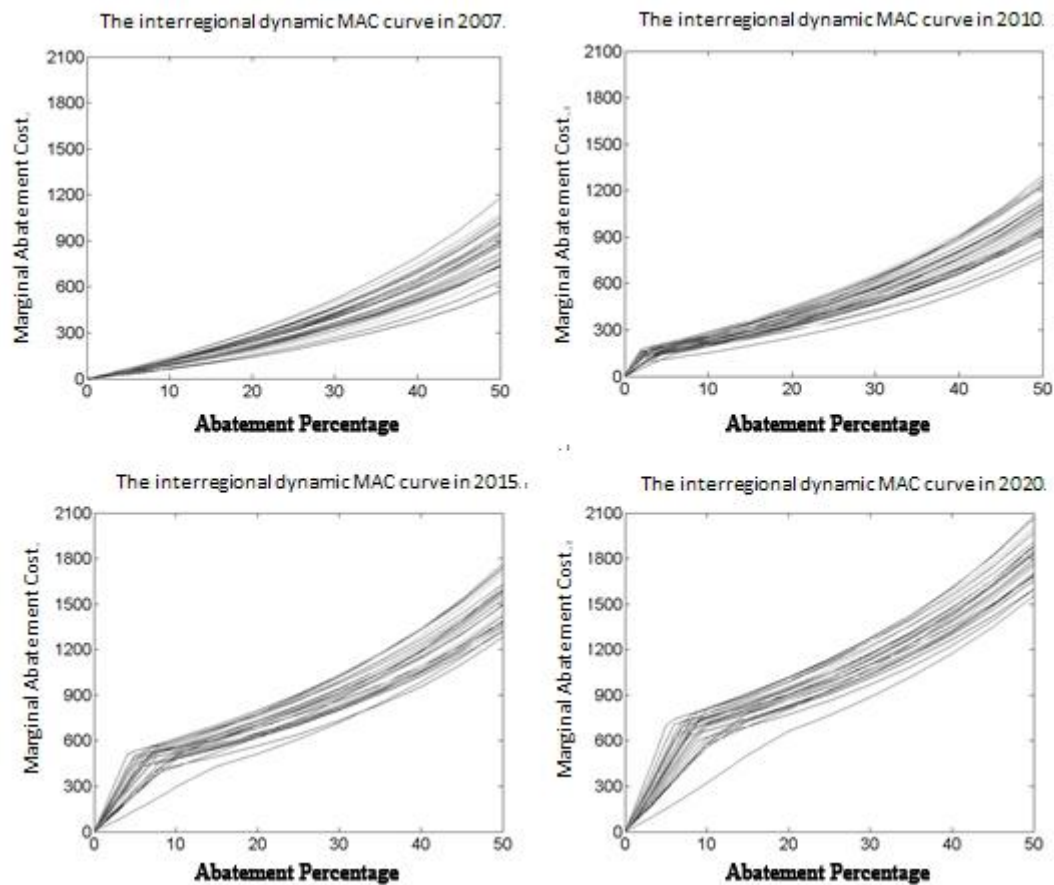


Figure 6 The comparison between different regions' dynamic MAC curves

Note: Each kinked line represents one region's MAC curve

Figure 6 shows the comparison of MAC curves among all regions in four years. As what has been mentioned previously, only the MAC curve of Qinghai province has quite different shape compared to other regions. According to equation(5), main reason is that Qinghai province has a relatively

low cost share of energy input, so the increase rate of abatement activity is also relatively low. Thus makes the MAC curve very similar to the traditional one. However, results in Figure 6 show that kink points occur after 2007 and these kink points change the shape of MAC curves greatly in year 2015 and 2020. Most kink points occur when emission reduction rate ranges between 4 to 10 percent in 2015 and ranges between 5 to 15 percent in 2020. Most of these differences are contributed by the mixed effects of cost share of energy inputs and changes in relative prices according to equation(5). Additionally, different emission intensity settings in BAU scenario also accounts for part of the differences.

2. Making policy choices between taxes and cap and trading system

To support the policy choices between tax and cap and trading system, we need to know the relative importance of various factors driving the appearance of kinked points. Basing on equation (3) to (5), which indicate the mechanisms of kink point, we can write the emission reduction rate corresponding to the kink point as a function of three kinds of elements, which are initial emission intensity, intensity target and energy input cost shares:

$$\begin{aligned} percent_{kink} &= f(Int, IntT, \mathbf{Share}) \\ \mathbf{Share} &= (Sh_{coal}, Sh_{oil}, Sh_{oilproduct}, Sh_{ele}, Sh_{heat}) \end{aligned} \quad (14)$$

in which $percent_{kink}$ is the emission reduction rate corresponding to the kink point. Int is the initial emission intensity and $IntT$ is the intensity target. $\mathbf{Share}$ is a vector of different energy input cost share which includes cost share of coal, oil, oil product, electricity and heat. We then apply Taylor expansion to equation (14) to get regression equation:

$$\begin{aligned} percent_{kink,it} &= \alpha_0 + \alpha_1 Int_{it} + \alpha_2 IntT_{it} \\ &+ \alpha_3 Sh_{coal,it} + \alpha_4 Sh_{oil,it} + \alpha_5 Sh_{oilprod,it} + \alpha_6 Sh_{ele,it} + \alpha_7 Sh_{heat,it} + \varepsilon_{it} \end{aligned} \quad (15)$$

Equation (15) is a panel data model and we get all data needed from simulation result of CGE model. The result of Hausman test reject null hypothesis and thus we set the model as fixed effect model. Moreover, we choose cross-section weighted least square method to estimate the model. This is motivated first by the intuition that regions are differentiated in many aspects such as production technologies and household preferences. Second, White test also suggest that the model shows heteroscedasticity. Regression results are shown in Table 1.

Table 1 Regression result of panel data

	Coefficient
C	0.089*** (0.034)
Int	0.112** (0.056)
$IntT$	-0.283*** (0.012)
Sh_{coal}	-3.632*** (0.374)
Sh_{oil}	6.969*** (1.078)
$Sh_{oilprod}$	0.405*** (0.130)
Sh_{ele}	0.350** (0.137)
Sh_{heat}	8.940*** (2.113)

*** and ** mean coefficient is significant at 1% and 5% level respectively

Not surprisingly, results in **Error! Reference source not found.** indicate that higher initial intensity target will lead to later occurrence of kink point and higher intensity policy target will delay the occurrence of kink point. This is consistent with the theoretical prediction shown in Figure 1.

Estimation results show that shares of different energy input contribute quite differently to the occurrence of kink point. Negative coefficient of Sh_{coal} indicates that increase in cost share of coal will cause intensity curve in Figure 1 become steeper and this change comes from larger substitution effect of coal input. Consequently, this effect moves the intersect point leftward which accelerate the occurrence of kink point. However, results show that all other energy inputs are opposite to coal and increase in cost shares of these energy inputs will delay the occurrence of kink point.

VI. Policy choice analysis

According to the Weitzman's rule, when the MAC curve appears to be relatively flat, it will be more efficient to adopt the quantitative policies such as emission trading, while it will be more effective to adopt the price policies such as carbon tax when the MAC curve appears to be relatively steep. Following the simulation results in this paper, the occurrence of kink points divide the MAC curve into two part -- one flat and another steep. Therefore, it is essential to take this result into

consideration when implementing the emission reduction policies.

In order to apply Weitzman's rule, we need to further identify the slope of MB curve. There is a consensus that the marginal damage from greenhouse gases is constant, which means a quite flat MB curve. However, when facing environmental problems, people are more likely to put more attention on regional air pollutions, this is especially true in China. As a result, when estimating MB curve, ancillary benefits of greenhouse gas reduction should also be taken into consideration. There are already many researches study the ancillary benefits of two environmental problems. Some of these studies use integrated environmental assessment model or sector specific analysis to investigate the co-benefit of climate change policy and regional air pollution control policy. (Syri et al., 2001; Alcamo et al., 2002; Mayerhofer et al., 2002; van Vuuren et al., 2006; Takeshita, 2012) More recently, a few researchers begin to study these co-benefit in China. Zhang et al. (2015) combines the energy conservation supply curves and GAINS model to study the co-benefit in China's cement industry. They find energy efficiency measures and end-of-pipe options in China can achieve emission reductions at relatively low cost. Dong et al. (2015) combine the AIM/CGE model with GAINS model to assess the co-benefit at China's provincial level. They find there exist co-benefits at provincial level and regions with higher GDP will get higher cost reduction co-benefits. All these studies show that when take ancillary benefits of greenhouse gas reduction into consideration, the new MB curve maybe not that flat.

Due to these uncertainties in estimating MB curve, we set a wide range of the slope of MB curve and make comparison between the slope of MB curve and MAC curve. The comparison result shows the conditions that price policies dominate, or at least, are better than quantity policies.

Table 2 Policy selection matrix between price policies and quantity policies

Year	Slope of MB curve, 10,000 yuan/percent										
	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
2007	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
2008	100%	20%	0%	0%	0%	0%	0%	0%	0%	0%	0%
2009	100%	37%	0%	0%	0%	0%	0%	0%	0%	0%	0%
2010	100%	57%	7%	3%	3%	0%	0%	0%	0%	0%	0%
2011	100%	63%	10%	7%	7%	3%	3%	0%	0%	0%	0%
2012	100%	77%	7%	3%	3%	0%	0%	0%	0%	0%	0%
2013	100%	80%	33%	30%	30%	27%	27%	7%	3%	0%	0%
2014	100%	97%	60%	53%	53%	50%	50%	33%	17%	10%	3%
2015	100%	97%	83%	80%	80%	73%	67%	57%	27%	17%	7%
2016	100%	100%	100%	97%	97%	97%	77%	63%	40%	27%	13%
2017	100%	100%	100%	100%	97%	97%	80%	67%	43%	27%	13%
2018	100%	100%	100%	100%	97%	97%	80%	73%	43%	27%	17%
2019	100%	100%	100%	100%	97%	97%	80%	73%	50%	27%	20%
2020	100%	100%	100%	100%	97%	97%	83%	73%	60%	33%	20%

In Table 2, each cell contains a number which is the percentage of regions which should take price polices according to Weitzman's rule. Light area in Table 2 means few region should adopt price instrument while dark area in Table 2 means most regions should adopt price instruments. When we take ancillary benefits of greenhouse gases reduction into consideration, the slope of MB curve may become even steeper. This means there are greater possibilities that real world will locate in the light area in Table 2. In this case, quantity instruments are definitely better than price instruments.

Next, we assume the slope of MB curve to be 3,000 yuan/percent. Then according to Weitzman's rule, we summarize the policy choices of each region in Table 3.

Table 3 Summarize of regions which should switch quantity policy to price policy

Year	Regions
2010	Hainan
2011	Henan
2013	Hebei, Jilin, Heilongjiang, Shanghai, Anhui, Jiangxi, Hunan, Chongqing
2014	Shanxi, Hubei, Guangxi, Sichuan, Guizhou, Gansu, Xinjiang
2015	Inner Mongolia, Liaoning, Jiangsu, Zhejiang, Shandong, Yunnan, Ningxia
2016	Beijing, Tianjin, Fujian, Guangdong, Shaanxi
2017	Qinghai

The results in Table 3 show that most regions entered the “steep slope” part of MAC curve between 2013 and 2014 which cause the slope of MAC curve become larger than that of MB curve. Therefore, under the assumption that the slope of MB curve is 3,000 yuan/percent, the simulation results will suggest imposing carbon taxes other than implementing emission permit trading scheme in all regions from 2016 to avoid extra economic efficiency loss under uncertainty.

VII. Conclusions

In this paper we introduce the kink point mechanism into a dynamic regional CGE model to simulate each province’s MAC curve in China. The shapes of MAC curve at regional level facilitate us to study the choice of carbon abatement policies based on the combination of this mechanism and Weitzman’s rule.

Firstly, we find that regional MAC curves shift upward over time which means the increase of abatement cost and the difference among MAC curves also become larger after year 2015. This is because the emission intensity targets go tighter in all regions and the result is consistent to our common sense.

Secondly, kink points occur to all regional MAC curves and these kink points have very different characteristics. When facing emission constraint, each region has to adjust its optimal production behavior by balancing the cost of abatement activity input and the cost of reducing output. The existence of intensity targets causes initial abatement activity cost to be higher than the cost of reducing output. These high costs cause the inconsistent behavior in reducing emissions and lead to the occurrence of kink points in MAC curves. Moreover, each regions’ emission intensity targets and cost share of inputs also affects the difference of kink points.

Thirdly, the choice of price policies or quantity policies is highly dependent on the shape of MB curve. Simulation results show that positions of kinked points of regional MAC curves shift rightward as time goes, resulting the actual reduction rate locate at the left side of kink points. The slope of MAC curve at the left side of kink point is higher than that at the right side, this indicates higher possibility to suffer more efficiency losses of adopting price control policies than quantity policies. Sensitivity analysis of slope of MB curve suggest that quantity instruments are only suitable when MB curve is steeper than a certain level.

Finally, we must pay attention that this paper only discusses the choice of two kinds of policies from the aspect of the shape of dynamic MAC curve. Other factors will definitely also affect the policy making decision, such as trading cost, income distribution effect, transfer effect and so on. All of these need to be further studied in the future.

VIII. Appendix

In this section, we will make some robust analysis about the MAC curve. As we have already discussed in the previous section, choice of policy instrument is mainly decided by the kink points of MAC curves. The occurrence of kink points is determined by three factors: emission intensity target, cost share of inputs and elasticity of substitution among inputs. Uncertainties of all three factors may affect the equilibrium result in CGE model. The uncertainties of the first two factors are related to model setting and parameter calibration and their affect is relatively small for the reason that both BAU scenario settings and cost share are drawn from existing policy announcement and real data. So the only uncertainty we should concern is from choosing free parameters such as elasticity of substitution. (Mansur and Whalley, 1984)

Generally, most free parameters in CGE model are chosen from empirical studies, both in regional level and industry level. However, these estimation results are high dependent on the specific regression models and data used by researchers. Thus the elasticity of substitution values used in CGE model may vary in a large range which may cause very different equilibrium results. In this section, we will conduct robust analysis of the elasticity of substitution among different energies which play the most important role in this paper.

In the CGE model, elasticity of substitution used in the CES function ranges from zero to infinity. However, in most research studies, this range is usually taken as from zero to six and most functions just take this value as one such as Cobb-Douglas function. For this reason, it is reasonably that we assume that the elasticity of substitution has an upper bound greater than zero.

Several methods have been proposed to do robust test on the uncertainty of free parameters in the CGE model.(Wigle, 1991; Harrison et al., 1993) These methods can be divided into five categories: limited sensitivity analysis, conditional systematic sensitivity analysis, unconditional systematic sensitivity analysis, Bayes method and extremum method. Here we adopt the limited sensitivity analysis method which includes the elasticity of substitution among energy inputs.

The elasticity of substitution among energies adopted in this paper is 0.5. We suppose the elasticity bears beta distribution $\sigma \sim Be(a,b)$ to better represent the boundary feature (Wang & Chen, 2006). The expectation value of is 0.5 and the standard deviation is 0.3. Besides, the upper bound and lower bound are 0 and 2 respectively. From these conditions we can calculate the value of two parameters:

$$f(x) = \frac{\Gamma(a+b)}{\Gamma(a)\Gamma(b)} \left(\frac{x}{2}\right)^{a-1} \left(1-\frac{x}{2}\right)^{b-1}, 0 < x < 2 \quad (16)$$

$$\frac{a}{a+b} = 0.5, \frac{ab}{(a+b)^2(a+b+1)} = 0.3^2 \quad (17)$$

From equation **Error! Reference source not found.**, we get a equals 11/6 and b equals 33/6. In our Monte Carlo simulation we assume a 10 percent emission reduction rate in year 2010 in Beijing as a representative due to the complexity of the whole CGE model. In the simulation, we draw elasticity of substitution from the beta distribution for 1000 times and solve the equilibrium results each time to get the distribution of marginal abatement cost.

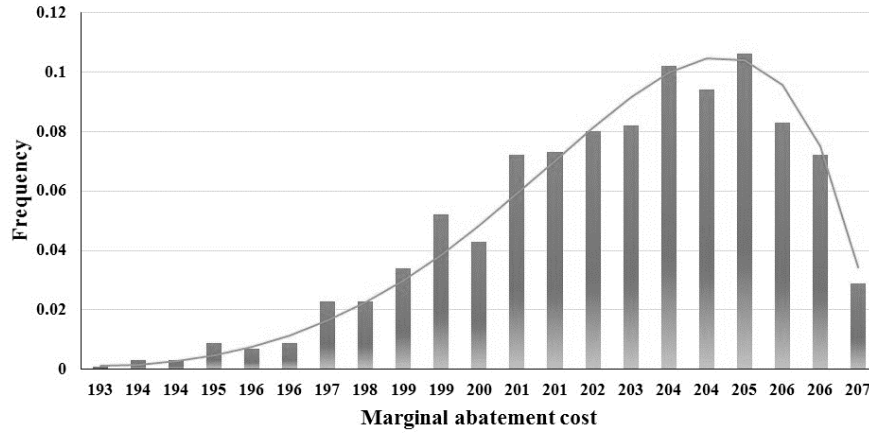


Figure 7 Distribution of marginal abatement cost in Beijing in 2010 under a 10% emission reduction

In Figure 7, the histograms is the simulation result and solid line is the linear transformation of the standard beta distribution. The scale coefficients of linear transformation come from the regression results of simulation results and the elasticity of substitution drawn from beta distribution shown in Table 2.

Table 2 Result of Regression Analysis of the Marginal Abatement Cost

Regression equation: $MAC = C + \text{beta} * \text{sigma} + \epsilon$		
	Constant	Slope
Estimation Value	206.791***	-9.074***
Standard Deviation	(0.00849)	(0.01444)

*** implicates it is significant at level 1%.

Table 3 Summary statistics of Monte Carlo Result

Index	Real Value	Sample value	Fitted value
Average	202.14	202.29	202.25
Standard Deviation	N/A	2.86	2.72
Coefficient of Variation	N/A	0.014	0.013

Table 3 gives three value of marginal abatement cost. Real value comes from original CGE model which has no standard deviation. Sample value is the average value of 1000 times simulation. Fitted value is the expected value of linear transformed beta distribution. We can see that all values are very close to each other which indicates sample mean value converges to the real value. The confidence interval of marginal abatement cost under the 95% significance level is [196.03,206.21]. From the perspective of percentage, this confidence interval is [-3.0%,2.0%] which is an acceptable range. Table 4 gives the corresponding confidence interval of marginal abatement cost under different emission reduction target rate:

Table 4 Corresponding Errors of Different Carbon Abatement

Percentage	Confidence Interval (95%)		Confidence interval of percentage	
	Lower Bound	Lower Bound	Lower Bound	Lower Bound
2%	63.06	75.62	-7.6%	10.8%
4%	129.40	132.50	-0.9%	1.4%
6%	164.45	172.80	-2.9%	2.0%
8%	179.94	189.14	-3.0%	2.0%
10%	196.12	206.19	-3.0%	2.0%

The results in Table 4 implies that the confidence interval converges rapidly to a stable range. In Beijing's case, the actual emission reduction rate in 2010 is 9.5% which means the confidence interval of its marginal abatement cost is stable enough to draw the conclusion of policy choice. This result show that the simulation results in our CGE model is robust and also reliable.

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