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Marginal abatement cost curve and optimized abatement trajectory of CO_2 emissions of China's petroleum industry

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Abstract: Assessing marginal abatement costs (MAC) of emissions improve the understanding of the extent of current CO_2 mitigation and provide regions and industries with information on how to mitigate emissions cost-effectively. This study proposes a hybrid method to evaluate MAC, which combines the strengths of bottom-up engineering methods and top-down economy-wide methods. A parametric directional distance function is employed to estimate MAC from an economic perspective, and the abatement level is further incorporated to generate increasing curves, which is similar to the outcomes derived from an engineering perspective. In addition, this method takes into consideration whether the abatement level exceeds the abatement potential with current production technologies so as to provide a more realistic estimation of the MAC curve. The proposed technique is applied in estimating the carbon emission MAC in China's petroleum industry. The estimation results indicate that: i) the MAC of China's petroleum industry would change from 9,821 Yuan/ton to 16,307 Yuan/ton when the abatement level increases from 1% to 50%; ii) this industry would spend 36.5 to 42.5 billion Chinese Yuan annually to achieve China's CO_2 reduction target proposed in the Intended Nationally Determined Contributions (NDCs); iii) assigning the CO_2 reduction targets based on the estimated MAC curves instead of the traditional grandfathering abatement target assignment would help to save additional 29.97% to 33.65% abatement cost for China's petroleum industry for achieving the NDCs. The MAC curves estimated in this study indicate more accurate relationships between abatement levels and abatement costs which provides the decision-makers both in industries and governments with a more reliable instrument to determine prices of emission permits, total abatement costs, and implementation strategies in an emission trading scheme.

Key words: Abatement potential; Abatement target; Carbon emissions; Directional distance function; Marginal abatement cost; Shadow price

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1 Introduction

Recently, the Intergovernmental Panel on Climate Change (IPCC) published the Special Report on Global Warming of 1.5℃. The report pointed out that global warming is likely to reach 1.5℃ above pre-industrial levels between 2030 and 2052 if it continues to increase at the present rate (IPCC 2018). Strengthening the measures to reduce carbon emissions is imperative for halting anthropogenic global warming. As the biggest emitter of carbon dioxide (CO_2) emissions, China has emitted about 9.1 billion tons of carbon emissions in 2015, which accounting for about 28% of global CO_2 emissions (Fan et al. 2019). China has made great efforts to carbon emission abatement. For example, China proposed the target of 40%~45% carbon intensity reduction from 2005 to 2020 and committed that the peak of carbon emissions will appear before 2030 (NDRC 2015; NDRC 2016). Carbon emissions are usually undesirable outputs in production activities, and the abatement measures of carbon emissions have costs. In other words, the carbon emissions abatement cost reflects the economic cost that society needs to pay to mitigate climate change. The assessment of marginal abatement cost (MAC) of a geographical region or an industry sector can improve its understanding of the current extent of carbon emission mitigation, which may help policy makers and entrepreneurs design more effective regional polices or mitigation measures to fulfill the abatement objectives cost-effectively.

Most studies separately use an engineering method or an economic method to estimate MAC. The MAC estimated from the engineering perspective is comprised of the investments and expenditures for the mitigation technologies, which is incurred when a production unit reduces one unit of CO_2. The engineering method stacks up the different amounts of carbon emission reduction achieved by mitigation technologies with the order of MAC, thus generating a step-wise MAC curve (presented in Online Resource 1), which provides the intuitive understanding on abatement potential and cost for policy makers and entrepreneurs. To sum up, one of the characteristics of the engineering method is this method pays attention to the information on the amount of abatement and the abatement cost for each reduction technology, and the other is the cost information estimated from this method depends on the amount of carbon emission abatement. Studies estimating the MAC from an economic perspective usually employ an economic model, which is different from the engineering perspective. Firstly, they utilize distinct databases and methodologies. The economic method employs the data of actual production activities with the consideration of the whole production process while the engineering method use an established technological database of reduction measurements (Aiken and Pasurka 2003). The economic model contains the key input and output factors of the production activities, and thus the more comprehensive characteristics of mitigation measurements are included in the estimation, for example, the recycling of resources and synergies among activities, whereas the engineering method just concentrates on the outcomes of abatement technology and investment costs. They also have a distinction in the results. The economic cost is a representative value while the engineering method yields curve-shaped information which presents the relationship between the carbon abatement and MAC straightforward. (Lee et al. 2014).

Based on the aforementioned discussion, the engineering method and the economic method often lead to different estimations which may confuse policy makers or entrepreneurs for capturing the real abatement cost. For example, Kiuila and Rutherford (2013) pointed out that the CO_2 emission abatement cost might be considerably overestimated by top-down economy-wide methods if a bottom-up abatement cost curve obtained by sector-specific methods is not included. To solve this problem, we here propose a new way to reconcile the methods from both the engineering and economic perspectives.

Specifically, we develop a model that incorporates the MAC of the economic method and the abatement levels of the engineering method, and thus, the MAC curve can be derived from this reconciled model. This model focuses on the strengths of two methods: (i) the MAC estimated by the economic method takes the entire production activities into account, and (ii) the engineering method provides information on the relationship between abatement levels and abatement costs. It demonstrates that these two methods are complementary rather than contradictory. The estimated MAC curve could indicate the relationship between the abatement levels and the abatement cost (for instance, the increase of the abatement levels will result in a growth trend in the MAC of carbon emissions), and could help to determine prices of emissions permits, total abatement cost, and regional or sectoral emissions in an emissions trading scheme (Klepper and Peterson 2004).

2 Literature review

2.1 Marginal abatement cost estimation from the engineering perspective

The estimation of MAC of the engineering method includes specific descriptions about alternative measures or technologies for mitigating carbon emissions, and the cost of each technology is obtained after considering the difference between a business-as-usual case and a low carbon scenario with respect to the abatement of emissions (Tomaschek 2015). Specifically, this estimation decomposes the existing measurement of carbon emission abatement into a few individual mitigation choices with distinct technological means, and prioritizes these options by which to achieve the reduction target in a particular year. Using the relationship between the MAC and carbon emission abatement, policy makers or entrepreneurs can determine the priority of carbon emission reduction technologies and the least cost choice to meet an ideal carbon emission reduction target.

There have been many studies on the engineering method for estimating carbon emission abatement cost in recent years. Enkivst and Naucler (2007) established an integrated fact base and related greenhouse gas reduction cost curves indicating the significance and cost of available abatement measures. Their analysis revealed some implications for the development of abatement measures. For example, establishing stable long-term incentives can encourage power enterprises to enhance greenhouse gas-efficient technology. Gnansounou et al. (2004) estimated maximum carbon emission abatement achievable by the natural gas combined cycle technology in electricity industry in Shanghai, and showed that the amount can reach 42.4MtCO_2 during the period of 2003~2030. Mao et al. (2013) reported the unit cost of CO_2 reduction and priority order of emissions reduction measures for the iron and steel industry in China. They also pointed out that the carbon capture and storage and the phasing out of outdated production capacity made contributions of 61% and 22% to the total reduction potential on CO_2 emissions in the steel industry, with the remainder being reduced by other technological abatement measures. Souza et al. (2018) estimated the Sao Paulo state's industry reduction potential on carbon emissions during the year of 2014~2030 on the basis of MAC curve. The results show that 50% of the technologies have negative MAC values and technologies of energy efficiency present the lowest cost with a weighted average value of -$122/ton of CO_2. Hasanbeigi et al. (2013) assessed several CO_2 abatement technologies of the iron and steel industry in China. The study shows that 60% of energy efficiency technologies are cost-effective.

2.2 Marginal abatement cost estimation from the economic perspective

The concept of shadow price is usually applied to denote the MAC derived from an economic method. Shadow price represents the opportunity cost of mitigating one unit of undesirable outputs. For policy makers, knowing the shadow price can help to determine the appropriate penalty rate, and for entrepreneurs that participating in the emission trading market, the assessment of shadow price can help them decide whether to buy or sell the emission allowance (Xu et al. 2010). Furthermore, many studies utilized the shadow price to reflect the necessity and effectiveness of multiple environmental regulations. For example, Rezek and Blair (2005) and Swinton (2004) all argued that the introduction of emission-trading mechanisms can accelerate the convergence of shadow prices among production units.

The shadow price estimation is based on the distance function, which has advantages in the estimation of the price of pollutants. It just requires the information on quantity data about the input and output elements in production process instead of detailed information about the abatement technology. The input and output distance functions are commonly used for shadow price estimation, in which, the output distance function is based on the proportional expansion in outputs with inputs held constant, whereas the input distance function is based on the proportional saving in inputs with outputs held constant(e.g. Färe et al. 1993; Coggins and Swinton 1996; Hailu and Veeman 2000; Kwon and Yun 1999; Lee 2005; Swinton 1998; Turner 1995; Wu and Ma 2018). In recent years, more and more studies chose the directional distance function (DDF) for estimation. The directional distance function is a generalization of the output distance function. It allows the desirable and undesirable outputs to change asymmetrically at the same time, which is more suitable for the actual production activities than the output distance function. In other word, DDF allows to increase the desirable outputs and decrease the undesirable outputs simultaneously, which has been widely utilized in energy and environmental efficiency evaluations (e.g. Chen et al. 2015; Du et al. 2015; Färe et al. 2006; Wang et al. 2018; Mekaroonreung and Johnson 2012; Wang et al. 2011; Beltrán-Esteve et al. 2014).

The estimation procedure of the DDF has two popular approaches: parametric approach and nonparametric approach. The nonparametric approach uses data envelopment analysis (DEA) method to estimate the shadow price. The strength of this approach is that there is no necessary to set a specific form of the production function, and it is flexible and simple in modeling and calculation, since the DEA is a simple linear programming. The nonparametric approach is frequently applied in empirical studies (i.e. Choi et al. (2012); Wang et al. (2018); Wang et al. (2019)). Nevertheless, there exists a weakness in this approach: the estimated function of the production frontier is not differentiable everywhere, and thus, a decision-making unit (DMU) located on the inflection point of the frontier will have multiple slopes and the shadow price will be affected (Lee and Zhang 2012). In this paper, we choose the parametric approach to estimate the DDF because of its differentiability on the production frontier. This approach also has been adequately applied in empirical studies (i.e. Du et al. (2016); Peng et al. (2018); Wang et al. (2017); Rødseth (2013); Färe et al. (2012)).

However, the estimation of MAC from economic models are limited in the lack of consideration for emission reduction targets. They just derived a single representative value of shadow price and failed to reflect the changing tendency of shadow price as the reduction targets increase. The model we propose in next section will provide more economic implications since it estimates the shadow price under various abatement levels and thus a MAC curve can be derived.

3 Reconciled model for marginal abatement cost estimation

We assume a production process using the inputs $x = (x_1, x_2, \dots, x_I) \in R_+^I$ to produce the desirable outputs $y = (y_1, y_2, \dots, y_V) \in R_+^V$ and undesirable outputs $b = (b_1, b_2, \dots, b_U) \in R_+^U$. Then, the production possibility set $P(x)$ can be defined as：

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

The basic assumptions of this production possibility set include the sets are compact with $P(0) = \{0,0\}$, and the free disposability in inputs, which means, if $x' \geq x$, then $P(x') \supseteq P(x)$. Additionally, other assumptions need to be imposed since we consider the production of both desirable and undesirable outputs. First, the null-jointness of y and b: if $(y, b) \in P(x)$, and b=0, then y=0. It implies that the undesirable and desirable outputs are produced jointly. Second, the weak disposability of y and b: if $(y, b) \in P(x)$ and $0 \leq \theta \leq 1$, then $(\theta y, \theta b) \in P(x)$. This assumption means that proportional abatements of desirable and undesirable outputs are feasible. The last is the free disposability of y: if $(y, b) \in P(x)$, then for $y' \leq y$, $(y', b) \in P(x)$. It implies the desirable outputs can be reduced without the reduction of undesirable outputs.

We employ the directional distance function to represent the production technology, which is defined as:

$$D_0(x, y, b; g_y, g_b) = max\{\beta: (y + \beta g_y, b - \beta g_b) \in P(x)\} \quad (2)$$

The value of this function corresponds to the distance between the observation and the production frontier, and the directional vector $g = (g_y, g_b)$ in this equation is the path by which the outputs can be adjusted to the frontier. A higher β implies higher technology inefficiency, which means the observation is further away from the boundary. If $\beta = 0$, it means the observation is located on the production frontier. The directional distance function inherits the properties from the $P(x)$. The illustration and mathematical properties of $D_0(x, y, b; g_y, g_b)$ are further presented in Online Resource 2.

The revenue function is employed to derive the shadow price. We define $p = (p_1, \ldots, p_V) \in R_+^V$ to denote the prices of desirable outputs and $q = (q_1, \ldots, q_U) \in R_+^U$ to denote the prices of undesirable outputs. Therefore, we can obtain the shadow price of the *u*th undesirable outputs in the equation (2). The ratio in this equation can be represented by the slop of the tangent line on the boundary. More details of this derivation can be found in Fare et al. (2006).

$$q_u = -p_v \cdot \left(\frac{\partial D_0(x,y,b;g)}{\partial b_u} / \frac{\partial D_0(x,y,b;g)}{\partial y_v} \right) \quad (3)$$

Based on the discussions in Section 2, we use the parametric approach to evaluate the directional distance function and select the quadratic form because of its twice differentiability and translation property. Moreover, many studies indicate that the quadratic form is suitable for distance function estimation, for example, Vardanyan and Noh (2006), Fare et al. (2008) and Fare & Vardanyan (2010). Suppose there are *n*=1, …, *N* units, then the directional distance function of unit *n* can be expressed as:

$$D_0 = (x_n, y_n, b_n; g_y, g_b)$$
$$= \alpha + \sum_{i=1}^{I} \alpha_i x_{in} + \sum_{v=1}^{V} \beta_v y_{vn} + \sum_{u=1}^{U} \gamma_u b_{un} + \frac{1}{2} \sum_{i=1}^{I} \sum_{i'=1}^{I} \alpha_{ii'} x_{in} x_{i'n} +$$
$$\frac{1}{2} \sum_{v=1}^{V} \sum_{v'=1}^{V} \beta_{vv'} y_{vn} y_{v'n} + \frac{1}{2} \sum_{u=1}^{U} \sum_{u'=1}^{U} \gamma_{uu'} b_{un} b_{u'n} + \sum_{i=1}^{I} \sum_{v=1}^{V} \delta_{iv} x_{in} y_{vn} +$$
$$\sum_{i=1}^{I} \sum_{u=1}^{U} \eta_{iu} x_{in} b_{un} + \sum_{v=1}^{V} \sum_{u=1}^{U} \mu_{vu} y_{vn} b_{un} \quad (4)$$

Following Aigner and Chu (1968), we use linear programming to estimate the unknown parameters. The parameters are chosen by minimizing the sum of inefficiency for each unit.

$$min \sum_{k=1}^{K} [D_0(e_n, y_n e b_n; g_y, g_b) - 0]$$

s.t. (i) $D_0(x_n, y_n, b_n; g_y, g_b) \geq 0,\ n = 1, \dots, N$

(ii) $\frac{D_0(x_n, y_n, b_n; g_y, g_b)}{\partial b_u} \geq 0,\ u = 1, \dots, U,\ n = 1, \dots, N$

(iii) $\frac{\partial D_0(x_n, y_n, b_n; g_y, g_b)}{\partial y_v} \leq 0, v = 1, \dots, V, n = 1, \dots, N$

(iv) $\frac{\partial D_0(x_n, y_n, b_n; g_y, g_b)}{\partial x_i} \geq 0, i = 1, \dots, I, n = 1, \dots, N$

(v) $\sum_{v=1}^{V} \beta_v g_{yv} - \sum_{u=1}^{U} \gamma_u g_{bu} = -1$

$\sum_{v'=1}^{V} \beta_{vv'} g_{yv'} - \sum_{u=1}^{U} \mu_{vu} g_{bu} = 0, v = 1, \dots, V$

$\sum_{u'=1}^{U} \gamma_{uu'} g_{bu'} - \sum_{v=1}^{V} \mu_{vu} g_{yv} = 0, u = 1, \dots, U$

$\sum_{v=1}^{V} \delta_{iv} g_{yv} - \sum_{u=1}^{U} \eta_{iu} g_{bu} = 0, i = 1, \dots, I;$

(vi) $\alpha_{ii'} = \alpha_{i'i}, i \neq i', \beta_{vv'} = \beta_{v'v}, v \neq v', \gamma_{uu'} = \gamma_{u'u}, u \neq u'$ (5)

The restriction (i) guarantees the feasibility of $P(x)$. The restrictions (ii), (iii), and (iv) are the monotonicity of b, y, and x, respectively. The restrictions (v) and (vi) imposes the translation property and symmetry conditions.

Before we connect the abatement level with the measure of shadow price, we should realize that for a production unit, it is quite common to undertake a reduction target of carbon emissions which is assigned by government or a voluntary objective set by itself. Based on this situation, taking the abatement level into consideration for shadow pricing model is significant for providing references on carbon abatement cost. Suppose there is a production unit A, it has two different reduction targets corresponding to higher carbon emissions (point A_1 in Fig. 1) and lower carbon emissions (point A_2 in Fig. 1) under the condition that their desirable outputs are at the same level. If we choose the directional vector $g = (g_y, g_b) = (1, 0)$, which means maximizing the desirable outputs, A_1 and A_2 can reach the frontier at the points A_1^* and A_2^* along the vector (note that A can reach the point A^*). From Fig. 1 we can find that the slope of point A_2^* is steeper than the point of A_1^*, in other words, A_2 has a higher shadow price than A_1. This phenomenon can be explained as the concavity of the production frontier. Additionally, we can also interpret this increasing tendency from an environmental efficiency perspective. Comparing to A_1, A_2 is more environmentally efficient since A_2 emits less carbon emissions than A_1 with the same amount of desirable outputs. Thus, it will be more difficult to additionally mitigate carbon emissions for A_2 than A_1, which leads to a higher shadow price for A_2.

[Insert Fig. 1 here]

According to the aforementioned discussion for the abatement level, there exists variation in shadow price as the reduction targets change for a production unit. The model we propose here can reflect the stepwise increasing pattern in the shadow price as the abatement level increases. At first, we employ the data on current inputs and outputs of production units to estimate the production frontier and use a parameter τ% to represent the change of abatement level. Then we obtain the abatement potential on carbon emissions for a production unit. The abatement potential is defined as the adjustment of carbon emissions (βg_b in equation 1) along the directional vector $g = (0, -1)$, which means the maximum carbon emission abatement without the adjustment of desirable outputs. Finally, the derivation of shadow price can be obtained as follows (here we assume one desirable output and one undesirable output for illustration convenience) in two different situations:

(i) The amount of carbon emission abatement is less than the abatement potential on carbon emissions. The point A and A_1 in Fig. 1 can illustrate this situation. The production unit A moves to A_1 by mitigating τ1% of its present emission level of CO_2, and after this movement, it will reach the point A_1^* on the frontier along g = (1, 0). The shadow price of production unit A with reduction target of r1% is the slope of A_1^*. Generally, if a production unit has r% reduction target, the corresponding shadow price is estimated as:

$$q_u = -p_v \cdot \left(\frac{\partial D_0(x,y,b(1-\text{r}\%);g)}{\partial b(1-\text{r}\%)} \Big/ \frac{\partial D_0(x,y,b(1-\text{r}\%);g)}{\partial y}\right) \qquad (6)$$

(ii) The amount of carbon emission abatement is larger than or equal to the abatement potential on carbon emissions. For instance, if a production unit A intends to mitigate τ3% of its present carbon emission level to reach A_3, but this movement cannot be satisfied with current technology level, in other words, A_3 is not included in $P(x)$, then, the desirable outputs need to be contracted through additional movement along the production frontier. In detail, a production unit A first mitigates carbon emissions until reaching the production frontier, and then it moves on the boundary of the production possibility set to meet the reduction target. Therefore, A_3^* is the point that A reaches at last, and the slope of A_3^* is the shadow price of A with τ3% reduction target. In general, if we estimate the shadow price in this condition, we have to additionally calculate the amount of desirable outputs of A_3^*. Since the point that achieves the target is on the boundary, we can express the function of this point as follows, where y' is the adjusted desirable output of A_3^* :

$$D_0 = \left(x, y', b(1-\tau\% \ ); g_y, g_b\right) = 0 \qquad (7)$$

Since the parameters of the production function have already been estimated through Equation (4) and Model (5), and $b(1-\tau\% \ )$ is known, the quadratic function (4) can be rewritten as follows:

$$\frac{1}{2}\beta_{11}y'^2 + (\beta_1 + \sum_{i=1}^{I}\delta_i x_i + \mu_{11}b(1-\tau\%))y' + \alpha + \sum_{i=1}^{I}\alpha_i x_i + \frac{1}{2}\sum_{i=1}^{I}\sum_{i'=1}^{I}\alpha_{ii'}x_i x_{i'} + \frac{1}{2}\gamma_{11}b(1-\tau\%)b(1-\tau\%) + \sum_{i=1}^{I}\eta_i x_i b(1-\tau\%) + \gamma_1 b(1-\tau\%) = 0 \qquad (8)$$

We can obtain the amount of adjusted desirable outputs y' by solving Equation (8), and then, the shadow price can be derived from:

$$q_u = -p_v \cdot \left(\frac{\partial D_0(x, y\prime, b(1-\mathrm{r}\%); g)}{\partial b(1-\mathrm{r}\%)} / \frac{\partial D_0(x, y\prime, b(1-\mathrm{r}\%); g)}{\partial y\prime}\right) \qquad (9)$$

Note that the above derivation of shadow price with the consideration of abatement level is not specific to directional vector g = (1, 0), while it is suitable for all other possible vectors $g = (g_y, g_b)$. Since a production unit may choose different carbon emission reductions measures such as the increase in technological efficiency, the enhancement of allocative efficiency, or the contraction of desirable outputs, represented by various directional vectors, one should not primarily assume which vector the production unit may select in actual production process. Besides, combining different reduction measures based on realistic situations may save the cost during the emissions reduction process (Fan et al. 2019). Thus, we estimate the average value of shadow price derived from directional vectors between g = (1, 0) and (1, –1) to provide a more representative and comprehensive estimation. We finally choose 46 directional vectors turning from g = (1, 0) and (1, –1) with a 1-degree increment, and these directional vectors mean that mitigating carbon emissions and expanding desirable outputs at the same time, which are ideal carbon emission reduction measures for the production unit.

4 Data and low carbon scenarios

4.1 Data

To demonstrate the model proposed in Section 3, we employ panel data of the petroleum processing and coking (PPC) industry (described in Online Resource 3) in thirty provinces in China during 2011 ~ 2015. We use three inputs: labor, fixed assets, and energy consumption; one desirable output: total output value; and one undesirable output: carbon emissions. The inputs and desirable output data are collected from the China Energy Statistical Yearbook, the China Statistical Yearbook, and China's provincial Statistical Yearbook. The amount of carbon emissions is derived from CEADs database (CEADs 2017). Based on these data, we first estimate the shadow price of carbon emissions corresponding to the abatement level which increases from 1% to 50% with a 1% increment each time to generate the MAC curve in PPC industry. Then we set two low carbon emission scenarios and evaluate the corresponding abatement costs for PPC industry among 30 provinces in China according to the actions on climate change by 2020 of China's Intended Nationally Determined Contributions (NDCs). Finally, we use the Representative Concentration Pathways (RCPs) database to set several low carbon emission scenarios and evaluate marginal abatement cost for PPC industry in Online Resource 4.

4.2 Two low carbon scenarios from China's Intended Nationally Determined Contributions

To accomplish the objective of keeping global average temperature rise to 1.5℃-2℃, 190 countries had submitted their Intended Nationally Determined Contributions (NDCs) in the United Nations Framework Convention on Climate Change Conference of the Parties in Paris. The NDCs are the voluntary emissions reduction targets of each individual signatory country. Based on the international responsibility, national circumstances, sustainable development strategy and development stage, China has determined some actions by 2020 in its NDCs including: i) To lower carbon intensity (i.e., carbon dioxide emissions per unit of GDP) by 40% to 45% compared to the 2005 level; ii) To increase the share of non-fossil fuels in primary energy consumption to around 15%; and iii) To increase the forest stock volume by 1.3 billion cubic meters and increase the forested area by 40 million hectares from the 2005 levels.

We consider the 40%~45% carbon intensity reduction target as two low carbon emission scenarios, and evaluate the relationship between the MAC and the reduction target. Each NDC scenario corresponds to a specific trajectory taken over time to reach the radiative forcing level. In specific, we assume that the reduction rate of carbon intensity is stable from 2005 to 2020, and the current carbon emission level is the level after emission reduction. The corresponding average annual rate of carbon intensity reduction for NDC 40% and NDC 45% are about 3.35% and 3.91%, respectively.

The business-as-usual (BAU) scenario considered in this paper is the current carbon emission level, and the difference between low carbon and BAU scenarios is the carbon emission abatement. The amount of carbon emission abatement of 30 provinces under NDC 40%

and NDC 45% can be found in Table 1.

[Insert Table 1 here]

5 Results

5.1 Marginal abatement cost curve of petroleum processing and coking industry

Fig. 2 depicts the pattern of average MAC of PPC industry of 30 provinces in 2011~2015, which increase as the abatement level increases. When the abatement level increases from 1% to 50%, the average value of MAC changes from 9,821 Yuan/ton to 16,307 Yuan/ton. The average values of MAC associated with 45%~50% abatement levels show sharply increasing costs indicating that it will cost a lot for further carbon emission reductions if the production units have released the reduction potential for carbon emissions sufficiently. When the reduction targets are assigned to production units, they should pay attention to whether the targets exceed their present ability. Moreover, since the carbon trading market has already been implemented in China, production units can determine how many carbon emissions should be mitigated by internal activities (e.g. adopting advanced technologies), and how many emissions could be mitigated by external activities (e.g. buying carbon emission allowance) by comparing its MAC curve with the market price of carbon. According to current situation of China's pilot carbon trading markets, the average price of carbon emission allowance during 2013~2016 is 33 Yuan/ton, which is much lower than the MAC we estimated. This phenomenon provides a support for introducing a national carbon trading market since at present the trading mechanism may help to significantly reduce the average abatement cost in this industry.

[Insert Fig. 2 here]

5.2 Marginal abatement cost of petroleum processing and coking industry under low carbon scenarios

According to the MAC curve and the carbon emission abatement we estimated in Section 5.1, we can assess the MAC under different reduction targets. Fig. 3 illustrates the relationship between the MAC and the abatement levels. The horizontal axis indicates the accumulated amount of carbon emission reductions under each NDC scenario, and the width of each column represents the reduction amount for each province. The meaning of abbreviations in Fig. 3 is presented in Table 1. We rank these reductions by the MAC levels from low to high, and generate a step-wise pattern that the MAC is higher as the accumulated amount of the reduction on carbon emissions increases. The data used in Fig. 3 are the average amount of carbon emission reduction and average level of MAC during 2011~2015 for each province. What can be seen from Fig. 3 is the ranks of the MAC for a specific province are same under two low carbon scenarios. For instance, no matter under which scenario, Heilongjiang is always the leftmost column, implying that this province has lowest MAC; while, for Inner Mongolia, its MAC is always ranked highest among thirty provinces under NDC 40% and NDC 45%. When the scenario changes from NDC 40% to NDC 45%, the average MAC of thirty provinces increases by 0.21% and the CO_2 abatement amount increases from 9.05 to 10.63 million tons, indicating that larger reduction targets correspond to more amount of CO_2 emission abatement and higher MAC. Moreover, the specific MAC of Shanxi increases by 1.18% indicating Shanxi's MAC is more sensitive to low carbon scenario switching than other provinces' MACs. One policy implication derived from this is that, on the one hand, the formulation of emission reduction targets requires comprehensive consideration of the factors such as emission reduction potential, emission reduction costs and social development. On the other hand, the central government should pay more attention to the provinces like Shanxi whose ranks of abatement costs are sensitive to different reduction targets, and correspondingly, adjust the assignment of carbon emission reduction burdens for these provinces timely when China's national reduction target changes.

[Insert Fig. 3 here]

6 Discussion

6.1 The importance of marginal abatement cost curve

MAC curve is a commonly used policy tool to indicate the emission abatement potential and related abatement costs. The advantages of the usefulness of the MAC curve could be summarized into three aspects. Firstly, the MAC curve could identify a win-win scenario for the abatement units and environment with the increase of the awareness and transparency of the emission reduction order and the associated abatement cost. Secondly, based on the precise volume of costs, some emission abatement options which may be very expensive could be identified. The MAC curve highlights these options, which may otherwise be overlooked in realistic. Thirdly, according to the aggregation level of the amount of emission abated, the MAC curve also clearly shows which one is the next abatement unit with more expensive cost to reach an additional emission abatement. The MAC curve could be seen as a guidance for abatement units when making the emission abatement option.

Two different methods can be distinguished to derive the MAC curve. On the one hand, the economic method explicitly shows in the graphical representation the cost for the emission abatement, while it do not capture the interaction between the abatement levels and the abatement costs, and neglects the behavioural aspects on emission abatement. On the other hand, the engineering method could provide the possibility to breakdown of emission abatement, but omits the details of production activities in the graphical representation. Therefore, an inappropriate estimation method would mislead and the limits of the MAC curve concept may lead to biased decision making.

In this paper, the estimated MAC curve could be derived from a reconciled model of the economic method and the engineering method. It indicates the relationship between the abatement levels and the abatement cost. Additionally, the abatement potential with current production technologies is also considered in the reconciled model to estimate a more realistic MAC curve. After combining the emission reduction targets, the optimized abatement trajectory of emissions could be obtained from the estimated MAC curve. In an emissions trading scheme, the estimated MAC curve could also help to determine the price of emission permit, total abatement cost, and total emissions of regions or sectors.

6.2 Total abatement cost of petroleum processing and coking industry under low carbon scenarios

Based on the MAC and the carbon emission reduction targets as shown in Fig. 3, we can also estimate the total amount of carbon emission abatement cost of each province to measure the pressure of carbon emissions reduction under two NDC scenarios. If we assume that the cost increases linearly when reducing carbon emissions, and the cost of reducing the first unit of carbon emissions is 0 while the cost of reducing the last unit of carbon emissions equals to the MAC, then the total amount of carbon emission abatement cost of each province is the half area of each column in Fig. 3. The results are reported in Table 1. It is obvious that the total cost of carbon emission abatement under NDC 45% scenario is higher than those under NDC 40% scenario accounting for 0.36% (Hainan, the lowest) and 16.35% (Chongqing, the highest) of the total output value of the PPC industry during 2011~2015; while the total abatement cost under NDC 40% accounts for 0.31% (Hainan, the lowest) and 13.94% (Chongqing, the highest) of the total output value.

In addition, if China achieves CO_2 reduction target under NDC 40%, it would spend 36.49 billion Yuan and the amount of CO_2 abatement will reach to 9.05 million ton. The abatement cost under NDC 45% is 42.47 billion Yuan; whereas the corresponding amount of abatement is 10.63 million ton. This result is in accordance with the assumption that stricter abatement task will inevitably lead to higher abatement cost. Furthermore, Table 1 shows that the abatement costs vary significantly across China's thirty provinces. Under NDC 40%, the total CO_2 abatement cost of 15 provinces in the PPC industry is less than its 1% total output value, whereas only the abatement cost of Chongqing's PPC industry is more than 10% of its total output value. These ranges under NDC 45% are also relatively obvious (0.36%~16.35%).

6.3 Optimized carbon emissions abatement trajectory of petroleum processing and coking industry

The MAC curve presents more comprehensive references than the single representative MAC value estimated by conventional economic method in most previous studies, since it combines entire production process and technological options for abatement. Therefore, the MAC curve can be applied in the disaggregation of total abatement target across regions, industries, and firms (abatement units). We use the MAC curve to optimize the CO_2 abatement trajectory of PPC industry for minimizing the total abatement cost, which may provide policy makers with some implications on allocating reduction targets. Firstly, we obtain each province's MAC of CO_2 abatement from 1% to 50% reductions of its present carbon emissions amount, through a 1% stepwise increasing in the amount of abatement, and rank the corresponding MACs in ascending order. Then, we allocate the reduction target to provinces according to the MAC ranks: provinces with lower MACs would have the priority to mitigate carbon emissions. Specifically, the maximum amount of CO_2 abatement a province can burden is its abatement potential under present production technology (i.e. βg_b in Equation 2).

Fig. 4 illustrates the aforementioned allocation scheme based on MAC order of thirty provinces; and the width of each column represents 1% of each province's carbon emissions (i.e. 1% carbon emission abatement mount) before emission reduction. From Fig. 4, we can see that China's thirty provinces totally have near 96 million tons of carbon emission abatement potential under the technology level before emission reduction (2011-2015); and this potential is much higher than the reduction targets of NDC 40% and NDC 45%. Table 2 presents the optimized CO_2 abatement trajectory in detail. In Table 2, not all the provinces would be assigned reduction targets, the provinces with lower MACs, like Heilongjiang and Shanxi, would undertake all reduction targets. By contrast, under the abatement trajectory presented in Section 5, which is disaggregated according to the carbon emissions level before emission reduction, every province needs to participate in the allocation of reduction targets. The difference on the total abatement cost between the optimized abatement trajectory (Fig. 4 and Table 2) and the conventional abatement trajectory in Section 5 shows the cost savings of abatement strategies derived from the MAC curve. In specific, under NDC 40%, the total abatement cost of optimized trajectory is 24.21 billion Yuan, which would be 12.28 billion Yuan lower than that of the conventional abatement trajectory, indicating a 33.65% abatement cost saving. Furthermore, the optimized trajectories under NDC 45% would also save abatement cost for 29.97% (12.73 billion Yuan). The results indicate that disaggregating the reduction targets based on the MAC curve instead of relying on the traditional grandfathering principle would help to save the total abatement cost. The advantage of MAC based carbon emission abatement target disaggregation over grandfathering abatement target assign provides the policy makers another option on policy instrument to cost-effectively mitigate global warming.

[Insert Fig. 4 and Table 2 here]

7 Conclusions

In this study, we propose a new reconciled technique that combines the MAC derived from an economic method and the abatement levels of an engineering method, and further provide the MAC curves indicating the relationship between the MAC and the emission reduction targets with the consideration of abatement potential. Applying the proposed technique, we estimate the MAC curve of petroleum processing and coking industry in China among thirty provinces during 2011~2015 and illustrate the relationship between the MAC and reduction targets under two low carbon scenarios (NDC 40% and NDC 45%). Our estimating results indicate that: (i) as carbon emission reduction target increases, the MAC will grow with an increasing rate. The MAC of PPC industry would increase by 66.04% (6486 Yuan/ton) when the abatement level increases from 1% to 50%. (ii) The sensitivity of carbon emission abatement costs to carbon emission reduction targets varies significantly among provinces. For example, Shanxi's MAC would increase by 1.18% when the low carbon development scenario switches from NDC 40% to NDC 45%, which is more sensitive than other provinces' MAC (which would just increase by 0.21% on average). (iii) The accumulated abatement costs in PPC industry also vary significantly across provinces but is in line with the theory that stricter abatement target leads to higher abatement cost. The abatement cost under NDC 45% would be 5.98 billion Yuan higher than the cost under NDC 40%, while the corresponding abatement target under NDC 45% would be 1.58 billion ton higher than the target under NDC 40%. (vi) Disaggregating the carbon emission reduction targets among China's provinces based on our estimated MAC curves of provinces instead of the traditional grandfathering abatement target assignment would help to save additional 33.65% and 29.97% abatement cost under NDC 40% and NDC 45%, respectively.

Further studies may need to estimate future carbon emission abatement cost with the prediction on future carbon emissions for the emitters (i.e., provinces, industrial sectors and firms), which can provide informative implications for policy making in future carbon emission reduction effort. For example, this could help policy makers to determine the prior provinces or industrial sectors to mitigate carbon emissions in China according to their lower marginal abatement costs and higher abatement potentials, so as to reduce the total abatement cost of carbon emissions and the whole society's cost for mitigating regional environmental change in China.

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Tables and Figures

Table 1 Amount of CO_2 abatement and proportion of total CO_2 abatement cost to total industrial output value for thirty provinces in petroleum processing industry under three low carbon scenarios of China's Intended Nationally Determined Contributions (NDCs) (2011~2015 average value)

Provinces	Abbreviation	Amount of CO_2 abatement (10^4 tone)		Proportion of total CO_2 abatement cost to total industrial output value	
		NDC 40%	NDC 45%	NDC40%	NDC 45%
Beijing	BJ	9.91	11.63	0.60%	0.71%
Tianjin	TJ	16.35	19.19	0.62%	0.73%
Hebei	HB	43.25	50.77	0.86%	1.01%
Shanxi	SX	126.94	149.00	2.17%	2.54%
Inner Mongolia	NMG	23.79	27.92	3.33%	3.91%
Liaoning	LN	35.79	42.01	0.54%	0.60%
Jilin	JL	3.85	4.51	1.06%	1.24%
Heilongjiang	HLJ	94.46	110.87	1.51%	1.79%
Shanghai	SH	26.76	31.41	0.74%	0.87%
Jiangsu	JS	17.52	20.56	0.35%	0.41%
Zhejiang	ZJ	20.38	23.92	0.48%	0.57%
Anhui	AH	2.99	3.51	0.40%	0.47%
Fujian	FJ	20.35	23.89	1.72%	1.93%
Jiangxi	JX	20.67	24.27	2.06%	2.43%
Shandong	SD	66.22	77.72	0.34%	0.39%
Henan	HN	61.33	71.98	1.84%	2.11%
Hubei	HUB	9.02	10.58	0.55%	0.65%
Hunan	HUN	16.26	19.09	0.78%	0.92%
Guangdong	GD	18.92	22.21	0.34%	0.40%
Guangxi	GX	4.22	4.96	0.33%	0.39%
Hainan	HAN	3.24	3.80	0.31%	0.36%
Chongqing	CQ	16.86	19.79	13.94%	16.35%
Sichuan	SC	67.71	79.48	3.23%	3.67%
Guizhou	GZ	16.36	19.21	6.36%	7.39%
Yunnan	YN	26.61	31.24	4.86%	5.71%
Shaanxi	SHX	54.84	64.37	1.27%	1.48%
Gansu	GS	17.37	20.39	0.97%	1.13%
Qinghai	QH	5.82	6.84	6.87%	8.01%
Ningxia	NX	8.69	10.20	1.77%	2.09%
Xinjiang	XJ	48.86	57.35	1.72%	2.01%

Table 2 Optimized CO_2 abatement trajectory of petroleum processing industry under the 40% and 45% target in China's Intended Nationally Determined Contribution (NDC) (2011~2015 average value)

Low carbon scenario	Province	Abatement level (%)	Marginal abatement cost (Yuan/ton)	Amount of CO_2 abatement (10^4 ton)	Total abatement cost (10^8 Yuan)
NDC 40%	Heilongjiang	19	5341.49	536.03	143.16
	Shanxi	10	5255.30	379.14	99.62
	Total	-	-	915.17	242.78
NCD 45%	Heilongjiang	22	5571.21	620.67	172.89
	Shanxi	12	5471.34	454.97	124.46
	Total	-	-	1075.63	297.36

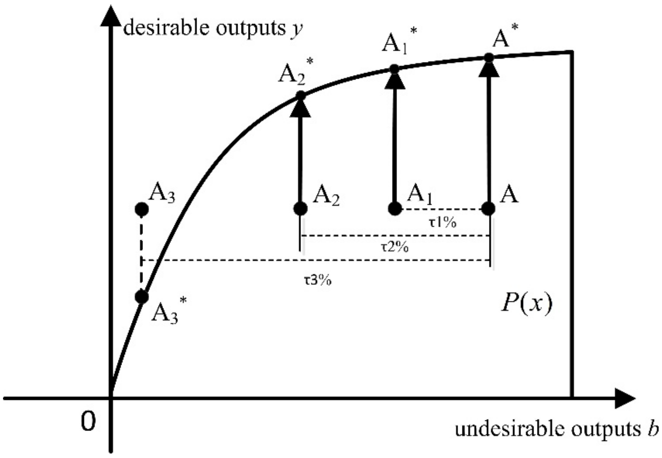


Fig. 1 Illustration of abatement level change

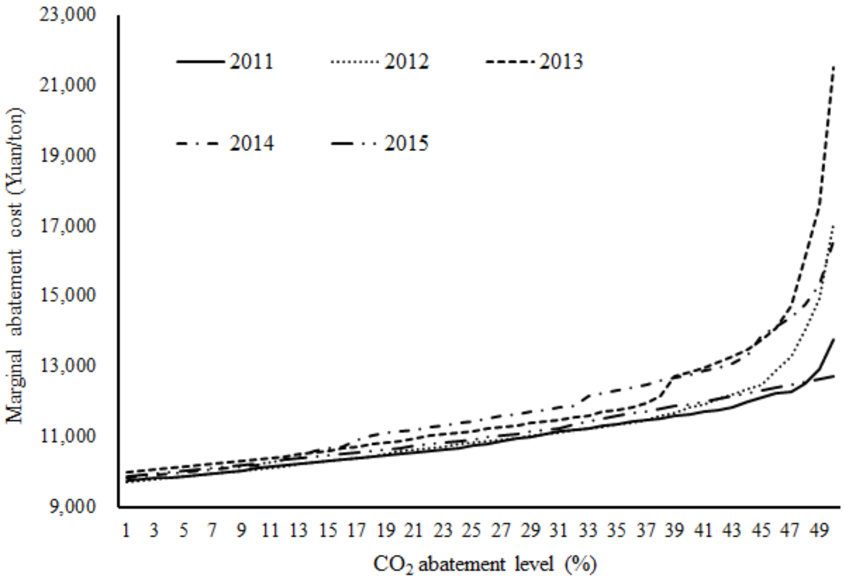
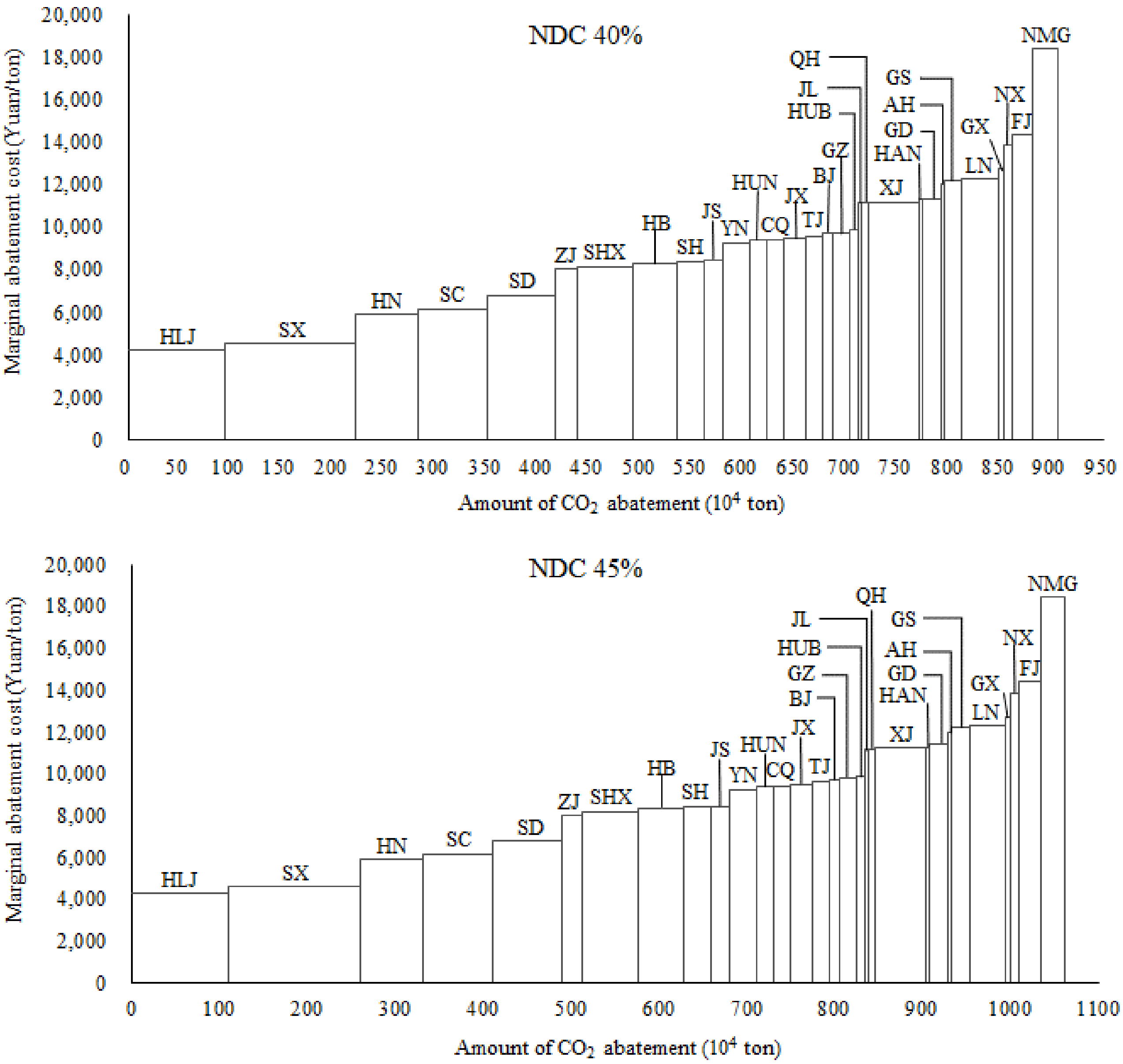


Fig. 2 Marginal abatement cost curves of petroleum processing industry (30 provinces average value)



Note: See Table 1 for full names of all abbreviations in the figure.

Fig. 3 Rank of marginal abatement cost associated with CO_2 abatement amount across 30 provinces under China's Intended Nationally Determined Contributions (NDCs) (2011~2015 average value)

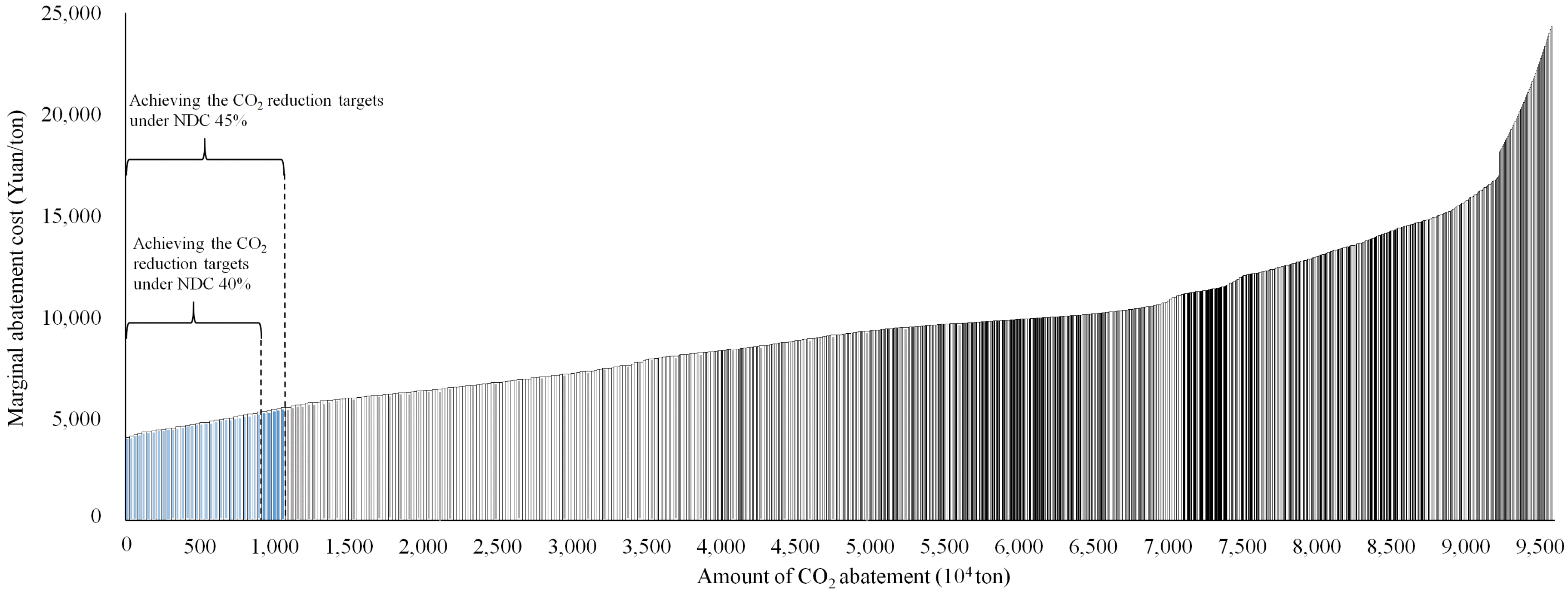


Fig. 4 Disaggregation of different reduction targets with 1% stepwise increasing on carbon emission abatement in different province (2011~2015 average value)