9-2012

Regional allocation of carbon dioxide abatement in China

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For all its limitations, however, the Copenhagen Accord is the first real step to fighting climate change in the 21st century. [1]

1. Introduction

During the 2009 Copenhagen conference, China pledged to reduce its carbon intensity (defined as a reduction in CO_2 per unit of GDP) by 40%-45% and set a target to be below 2005 levels by 2020. To continue and reinforce the energy-saving and emission-reduction strategy that began in the 11th five-year plan (2006-2010), the carbon intensity target will be integrated into the national 12th five-year plan (2011-2015). This raises an important issue: what is the best way to allocate the national CO_2 reduction goal among provinces or industries?[1] Earlier allocation procedures of energy-saving and emission-reduction targets in the 11th five-year plan relied on each province's proposals.[2] There is no bottom-up analysis of energy saving potential [3] or cost-benefit analyses to guide the allocation. Therefore, the allocation is controversial from the perspectives of equity and efficiency [4]. Recently, the National Development and Reform Commission (NDRC) recognized that the allocation of energy-saving and emission-reduction targets was not systematically set in the 11th five-year plan [5]. In the 12th five-year plan, more attention should be given to establishing targets that take into account differences among provinces [3].

[1] In the UN Climate Change Conference in Tianjin, which was held on October 22, 2010, before the COP16 in Cancun, the experts from China's think-tank of energy policy express their opinions on the allocation of CO_2 intensity in the 12th five-year plan. The debate was between region-based allocation and industry-based allocation. The concern on the region-based allocation of CO_2 intensity is that it may hamper the domestic carbon market in the future, partly a result of market segmentation and rising transaction costs. The problem with the industry-based plan is that the unbalanced technology development among regions will make it unfair to the undeveloped regions. The Chinese government has experience in regional allocation of SO_2, and therefore we predict that it will adopt the regional allocation plan with considering more differences among the regions in the future [2].

[2] The central government first requested each province propose its own target. Most provinces proposed to follow the central government's target of 20 percent, but four provinces proposed higher targets, and seven provinces proposed lower targets. Then the National Development and Reform Committee accepted those provinces that committed to a 20 percent or higher reduction and negotiated for higher targets with provinces that had committed to less than 20 percent. See details in the World Bank's report, pp. 37-38 [4].

Many equity principles have been proposed based on the equity perspectives and principles, which largely focused on the fairness of resource allocation and burden-sharing across nations [6]. These principles normally fall into three categories, allocation-based principles (focus on equitable initial distribution), process-based principles (the correct process of cost allocation) and outcome-based principles (the final allocation of the net benefit and cost). A successful criterion should be effective and implementable [7]. Among these equitable distribution principles, the idea of making per capita CO_2 emissions the basis for equitable burden sharing is a much-discussed option favored by many developing countries [8]. The "Contraction and Convergence" schemes from the Global Commons Institute [9] and the Brazilian proposal made during the Kyoto Protocol negotiations, are both results of this principle. However, there may be opportunities to use this criterion in combination with other rules because no single principle can be expected to resolve this issue [8, 10].

Most literature focuses on the schemes of CO_2 emission allocation among nations [11, 12,13]. Few studies address the regional allocation by country. Wei and Rose [14] built a nonlinear programming model to minimize the total energy conservation cost, and then proposed an interregional energy conservation-quota trading scheme in an efficient and equitable manner in China. Their simulation results suggest that this tradable quota system among regions can help China not only achieve the goal of energy conservation in a cost-effective way, but also stimulate and balance regional development.

Differing from Wei and Rose [14], the purpose of the paper is determining how to allocate CO_2 abatement among regions. Specifically, we aim to identify which province has a higher (lower) capacity to undertake more (less) burden, rather than to calculate how much CO_2 should be reduced. We propose a CO_2 Abatement Capacity Index (ACI) to evaluate each province's responsibilities and abilities regarding climate change mitigation using a weighted equity and efficiency index. The results show that a large gap exists between CO_2 reduction potentials and marginal abatement costs in various provinces and regions. The final ACI rankings may vary greatly and depend on the policymakers' preferences between equity and efficiency. However, some provinces, such as Inner Mongolia, Shanxi, Ningxia and Shanghai can be identified to take increased loads regardless of preferences, contrarily, Jiangxi, Guangxi, Hainan, and Yunnan should be distributed less loads.

This paper is organized as follows. Section 2 introduces the methodology. Section 3 describes the variables and data. Section 4 constructs the CO_2 Abatement Capacity Index and examines the provincial difference of CO_2 abatement potential. The conclusion follows in Section 5.

2. Methodology

The traditional neoclassical production model does not include an undesirable output such as pollution. This is mainly because there is no market price for this undesirable output. The distance functions and Data Envelopment Analysis (DEA) are two commonly-used methods to handle this problem [15].[3] The distance function approach enables the production modeling of a multi-input and multi-output technology when the prices are not available [21, 22, 23]. However, it needs a pre-determined function form to estimate the distance function as a frontier, and efficiency is measured in a fixed direction. To overcome this shortage, Chung et al. [24] developed a directional distance function, which is a generalization of Shephard's distance function and encompasses all known distance functions [25]. It can be estimated by both parametric and non-parametric DEA methods, which have been used to

[3] There are indirect and direct approaches to incorporating undesirable outputs into the production function. An indirect way is to shift undesirable outputs to inputs [16] or inversely transform the undesirable outputs [17, 18, 19]. The indirect approach inverts the undesirable output values to "normal" ones while keeping the original technology set. In contrast, the direct approaches keep the original output data unchanged but modify the assumption of the technology set to treat the undesirable outputs appropriately [20].

evaluate environmental performance across firms [26, 27] and to compare environmentally sensitive productivity across regions/industries [28] and across countries [29].

Although the directional distance function has many desirable features, it does not incorporate input and output slacks, which are an important source of inefficiency and may result in a biased estimation [30, 31]. This paper exploits an extended Slacks-Based Measure (SBM) of efficiency DEA model proposed by Cooper et al. [32].[4] It directly employs input and output slacks in production of an efficiency measurement. The advantage of this approach is that it is a non-radial and non-oriented model that can capture the whole aspect of inefficiency. This property is particularly attractive as we are interested in the reduction of undesirables rather than the increase of desirables. In addition, the DEA model constructs a non-parametric envelopment frontier over all sample data such that all observed points lie on or below the frontier [33], which does not require the imposition of a functional form on the underlying technology [23]. The points lying on the frontier are regarded as the best performers and thus become the benchmark line relative to other sample points.

We denote the input, desirable output and undesirable output for *n* decision-making units (DMUs) by the three vectors, $x \in R^m$, $y \in R^{s1}$, and $b \in R^{s2}$, respectively. The environmental production possibility set is defined by

$$P = \{(x, y, b) | \; x \geq \boldsymbol{X}\lambda, \;\; y \leq \boldsymbol{Y}\lambda, \;\; b \geq \boldsymbol{B}\lambda, \lambda \geq 0\}, \tag{1}$$

where $\lambda \in R^n$ is the intensity vector, $\boldsymbol{X}$ is a (m×n) matrix of inputs, $\boldsymbol{Y}$ is a (s_1×n) matrix of desirable outputs, $\boldsymbol{B}$ is a (s_2×n) matrix of undesirable outputs, and $\boldsymbol{X},\boldsymbol{Y},\boldsymbol{B} > 0$. Assuming that the technology generates constant returns to scale (CRS), the extended SBM model with undesirable outputs is represented below.

[4] The model employed here is consistent with the directional distance function; as seen later, we keep the desirable output constant and estimate the excessive inputs and undesirable outputs. This is a special case employing a directional vector $(g_x,g_y,g_b)= (-x,0,-b)$.

$$\rho^* = \min \frac{1-\frac{1}{m}\sum_{i=1}^{m}\frac{s_i^-}{x_{i0}}}{1+\frac{1}{s_1+s_2}\left(\sum_{r=1}^{s1}\frac{s_r^y}{y_{r0}}+\sum_{r=1}^{s2}\frac{s_r^b}{b_{r0}}\right)} \quad (2)$$

$s.t.\ x_0 = X\lambda + s^-$

$y_0 = Y\lambda - s^y$

$b_0 = B\lambda + s^b$

$s^- \geq 0, s^y \geq 0, s^b \geq 0, \lambda \geq 0.$

The vectors $s^- \in R^m$, $s^y \in R^{s1}$, and $s^b \in R^{s2}$ correspond to excesses in inputs, shortages in desirable outputs, and excessive undesirable outputs, respectively. The objective value in function (2) satisfies $0 < \rho \leq 1$. A DMU_0 (x_0,y_0,b_0) is efficient if and only if $\rho = 1$. In such an optimal case, all input and output slacks equal zero compared with other inefficient DMUs.

2.1 Undesirable output abatement potential model

If the DMU_0 is inefficient, it can be improved and become efficient by reducing the surplus input $\boldsymbol{s^-}$, increasing the desirable outputs $\boldsymbol{s^y}$, and reducing the excesses in undesirable outputs $\boldsymbol{s^b}$. For the inefficient DMU_0 (x_0,y_0,b_0) and its projection $DMU_0^*(x_0^*,y_0^*,b_0^*)$ in the frontiers, the following relationships exist:

$$x_0^* = x_0 - s^- ,\ y_0^* = y_0 + s^y,\ \ b_0^* = b_0 - s^b. \quad (3)$$

The efficiency of undesirable output will be b_0^*/b_0 [31].[5] Here we define the Feasible Abatement ($\boldsymbol{FA_{i,t}}$) and Abatement Potential ($\boldsymbol{AP_{i,t}}$) of undesirable output for sample *i* at period *t* as follows:

$$FA_{i,t} = s_{i,t}^b \quad (4)$$

$$AP_{i,t} = \frac{s_{i,t}^b}{b_{i,t}} = 1 - \frac{b_{i,t}^*}{b_{i,t},} \quad (5)$$

where ***FA*** expresses the slack of undesirable outputs that can be reduced by efficiency improvement toward the frontier, and ***AP*** measures the inefficiency level of undesirable outputs and its value between 0 and 1. A higher value indicates greater inefficiency and

[5] According to the definition of Farrell [34], input efficiency equals the ratio of minimum-to-actual input usage, while output efficiency equals the ratio of actual-to-maximum potential output.

greater potential of reducing the undesirable outputs [35]. It should be noted that a zero value of ***AP*** does not imply that the DMUs are perfect and without any excessive undesirable outputs or inefficiency during the production process. Rather, it indicates that the DMUs are Pareto-Koopmans efficient among all of the comparison samples.

2.2 Undesirable output shadow price model

The dual linear program (LP) of function (2) can be represented as follows:

$$\max u^y y_0 - v x_o - u^b b_0 \tag{6}$$

$$s.t.\ \ u^y Y - vX - u^b B \leq 0$$

$$v \geq \frac{1}{m}[1/x_0]$$

$$u^y \geq \frac{1+u^y y_0 - v x_0 - u^b b_0}{s}[1/y_0]$$

$$u^b \geq \frac{1+u^y y_0 - v x_0 - u^b b_0}{s}[1/b_0],$$

where $s=s_1+s_2$; the dual variables $v \in R^m$, $u^y \in R^{s1}$, and $u^b \in R^{s2}$ can be interpreted as the virtual price of inputs, desirable outputs and undesirable outputs, respectively. Assuming that the absolute shadow price of a marketable desirable output is equal to its market price, the relative shadow price of undesirable output with respect to desirable output can be expressed as [21, 26]

$$p^b = p^y \cdot \frac{u^b}{u^y}. \tag{7}$$

The shadow prices reflect the tradeoff between desirable and undesirable [21]. This can be interpreted as the marginal abatement cost [22, 36].

3. Variables and Data

The data cover 29 provinces for the period 1995-2007.[6] The production of GDP (*Y*) requires capital stock (*K*), labor force (*L*), and energy consumption (*E*) as inputs and, as a byproduct, yields one undesirable output, CO_2 emission (*B*). GDP deflates to the constant 2005 price. The labor input is calculated as the value of employment at the end of the current year; both values are obtained from the *China Statistical Yearbook* [37]. The data on energy consumption are collected from the *China Energy Statistical Yearbook* [38] .The capital stock is unavailable in any statistical yearbook, and therefore, we have to estimate this using the following perpetual inventory method:

$$K_{i,t} = I_{i,t} + (1 - \delta_i)K_{i,t-1,} \quad (8)$$

where $I_{i,t}$, δ_i and $K_{i,t}$ represent gross investment, depreciation rate, and capital stock for province *i* at time *t*, respectively. Here we select 1952 as the initial capital stock, as provided by Zhang et al. [39], and extend the capital stock serial to 2007. All serial data are converted to 2005 prices.

The data on CO_2 emission at the province level are not available. Based on the criteria published by the International Panel on Climate Change (IPCC) [11] and the National Coordination Committee Office on Climate Change and Energy Research Institute of NDRC [40], we estimate the CO_2 emissions emitted through the burning of fossil fuels by the following formula:

$$CO_2 = \sum_{i=1}^{6} E_i \times CF_i \times CC_i \times COF_i \times (44/12), \quad (9)$$

where *i* is the index of different types of fossil fuel, including coal, gasoline, kerosene, diesel, fuel oil, and natural gas. E_i, CF_i, CC_i, and COF_i represent the total consumption of fuel *i*, the

[6] There are 31 provinces, autonomous regions, and municipalities on the Chinese mainland. This study does not include Hong Kong SAR, Macao SAR or Taiwan Province. We combine Chongqing, the fourth municipality in China, with the Sichuan Province because the former was part of the Sichuan Province before 1997. Tibet is excluded because of the absence of energy data.

transformation factor, the carbon content of fuel *i*, and the carbon oxidation factor, respectively. 44/12 is the ratio of the mass of one carbon atom combined with two oxygen atoms to the mass of an oxygen atom. In addition, the CO_2 emissions from cement production are calculated by multiplying the quantity of cement production of each province by the carbon dioxide emissions coefficient of cement. All the data of energy consumption are taken from the energy balance tables by region in the *China Energy Statistical Yearbook* [38]. The data of cement production are taken from various *Statistical Yearbooks* of each province over various years.

The descriptive statistics for input and output for China and three regions are presented in Table 1. [7] The mean and standard deviation of GDP and capital stock in the eastern region are much higher than in the central and western regions. Meanwhile, the eastern area consumes the largest amount of energy and emits the most CO_2.

Table 1
Summary Statistics for Inputs and Outputs in China, 1995–2007

Region	Inputs			Desirable output	Undesirable output
	Capital (billion Yuan in 2005 prices)	Labor (10000 people)	Energy (10000 tons of coal equivalent)	GDP (billion Yuan in 2005 prices)	CO_2 emission (10000 tons)
China	9194.6 (8443.6)	2238.8 (1570.3)	6525.6 (4676.4)	4804.9 (4523.8)	12373.7 (8941.2)
#East	13908.9 (10569.7)	2286.1 (1569.4)	8261.2 (5830.7)	7457.4 (5752.0)	15483.5 (11310.1)
#Middle	7521.3 (4618.1)	2649.0 (1332.0)	6694.1 (3056.4)	4177.1 (2267.3)	13105.6 (5956.3)
#West	5347.5 (5098.3)	1858.7 (1666.0)	4481.5 (3359.4)	2389.3 (2264.3)	8367.4 (6046.1)

Source: Authors' calculation

[7] The east region includes Beijing, Tianjin, Hebei, Liaoning, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong and Hainan. The middle region includes Shanxi, Jilin, Heilongjiang, Anhui, Jiangxi, Henan, Hubei and Hunan. The west region includes Inner Mongolia, Guangxi, Sichuan, Guizhou, Yunnan, Shaanxi, Gansu, Qinghai, Ningxia and Xinjiang.

4. Empirical Results

This study employs the DEA Solver Pro 5 to solve the linear program problem. First, we calculate the CO_2 abatement potential and CO_2 shadow price. Then, we construct the CO_2 Abatement Capacity Index from equity and efficiency principles, and finally, we investigate the determinants of the CO_2 abatement potential among provinces.

4.1 CO_2 abatement potential

Table 2 lists the CO_2 abatement potential by province and region. The whole sample period is divided into two stages (1995-2001 and 2002-2007).[8] Column (I) presents the provincial feasible abatement volume of CO_2. The zero values of CO_2 abatement potential in column (II) for Beijing, Shanghai, and Guangdong indicate that these provinces are relatively efficient and lie on the frontier compared with other provinces. The zero values in columns (I) and (II) do not mean that there is no inefficient production and reduction space of CO_2 emission, but imply that these efficient provinces perform the best and cannot further improve their efficiency compared with the other provinces. In contrast, the large values of potential abatement for Guizhou, Ningxia, Inner Mongolia, Gansu, Xinjiang, etc., which are mostly located in the western region, reveal that these provinces emit excessive CO_2 due to production inefficiency during this period. In other words, there is a greater opportunity to reduce surplus CO_2 emission by efficient improvement in production for these provinces. In addition, we observe that many provinces' feasible abatement volumes and abatement potentials increase after 2002. For some provinces like Shanxi, its average abatement potential increases from 38% during 1995-2001 to 72% during 2002-2007. It indicates that efficiency degeneration and inefficient CO_2 emission has occurred since 2002. This observation is consistent with the research on the energy intensity where it declines

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[8] According to NBS's statistical data, the energy intensity (measured as China's energy consumption per GDP) is declining during the period 1980-2002 and rising after 2002. Considering both energy intensity and CO_2 abatement potential that reflects the utilization efficiency, one referee suggests we check for a dramatic difference before and after 2002. We verify this result and later we use the year 2002 as a dummy variable in econometric analysis for break-point test.

continually to the lowest point in 2002 and then rises. This efficiency degeneration mainly resulted from the accelerated industrialization and urbanization process and infrastructure development since 2002, which accompanies a high expansion of energy-intensive sectors and energy-consuming investment [3, 41, 42].

The values in column (III) are used to evaluate the impact of the regional abatement scale on the whole country. In the period 1995-2007, the CO_2 feasible abatement of Hebei, Shandong, Inner Mongolia, Liaoning, Henan, Shanxi, Sichuan, and Guizhou account for 55% of the national feasible abatement. If we investigate the period from 2002 to 2007, there are seven provinces with values higher than 5%, which include Shandong, Hebei, Inner Mongolia, Shanxi, Henan, Liaoning and Guizhou. These provinces contribute up to 51.2% of the whole CO_2 feasible abatement and have a greater influence on the national goal.

The final summarized statistics in Table 2 compare the potential abatement by regions. The eastern region (29%) ranks lowest in terms of potential abatement and is the most efficient in production. The western region (56%) has the greatest CO_2 abatement potential due to production inefficiency. On average, the overall potential reduction of CO_2 was 41% during the period 1995-2007. That is, 41% emissions, equivalent to 153.78 million tons of CO_2 per year, can be cut if each province can perform as efficiently as Beijing, Shanghai, and Guangdong. Among the three regions, the middle region contributes 35% to the national feasible abatement, while the eastern and western regions contribute 33% and 32%, respectively.

4.2 CO_2 marginal abatement cost

The marginal cost (Yuan in 2005 prices) of CO_2 reduction (ton) by province and region are listed in Table 3. Over the entire period of 1995 to 2007, Beijing has the highest average marginal abatement cost (266.5 Yuan/ton), while Shanxi, the main coal-producing area in China, has the lowest (31.1 Yuan/ton). Shandong registers the greatest negative change in the average marginal abatement cost; it decreased from 137.2 Yuan/ton during 1995-2001 to 26.5 Yuan/ton during 2002-2007. Shanghai's average marginal abatement cost increased the most, climbing from 127.1 Yuan/ton in stage 1 to 197.3 Yuan/ton in stage 2. It indicates that it is becoming less expensive to reduce additional CO_2 emissions in Shandong, while becoming more expensive in Shanghai.

The bottom three rows of Table 3 show the results by region. The CO_2 shadow prices vary widely across regions. On average, the highest marginal abatement cost with respect to CO_2 is observed in the east region (157.6 Yuan/ton) during the whole period. The middle region has the second highest shadow price (98.1 Yuan/ton) registered since 1996. The western region shows the lowest marginal cost of CO_2 (79.9 Yuan/ton). For the whole country, the shadow price of a marginal decrease in CO_2 emissions increased from 94.4 Yuan/ton in 1995, reached the peak at 139.5 Yuan/ton in 2002, and then declined. Its trajectory is also consistent with the trend of energy intensity and CO_2 abatement potential, which was caused mainly by accelerated urbanization and industrialization since 2002.[3, 41, 42]

4.3 CO_2 abatement capacity index

There are numerous studies that contribute to the equity criteria for global warming policy. Rose et al. [43] distinguished allocation-based, outcome-based and process-based criteria. However, among these principles, the developing countries tend to favor egalitarian or per capita distribution, while developed world prefer sovereignty or grandfathering principle [6, 44]. Recognizing that most of these principles can be further specified, here we follow Pan (2003) in that we concentrate on "egalitarian" and "ability to pay" principles which developing countries favored [6].

Table 2

CO_2 abatement potential by provinces and regions

Province	(I) CO_2 Feasible abatement per year (10000 tons/year)			(II) CO_2 Abatement potential (%)			(III) Contribution to overall FA (%)		
	1995-2001	2002-2007	1995-2007	1995-2001	2002-2007	1995-2007	1995-2001	2002-2007	1995-2007
Beijing	0	0	0	0	0	0	0.0	0.0	0.0
Tianjin	2109	2157	2132	44	31	36	2.0	1.1	1.5
Hebei	10549	16104	13113	55	54	54	10.2	8.3	9.0
Shanxi	4599	14293	9073	38	72	58	4.4	7.3	6.2
Inner Mongolia	5755	15018	10030	69	74	72	5.6	7.7	6.9
Liaoning	9342	10850	10038	57	51	54	9.0	5.6	6.9
Jilin	5071	6826	5881	61	58	59	4.9	3.5	4.0
Heilongjiang	6504	6237	6380	57	45	51	6.3	3.2	4.4
Shanghai	0	0	0	0	0	0	0.0	0.0	0.0
Jiangsu	3954	8436	6023	22	27	25	3.8	4.3	4.1
Zhejiang	1445	6932	3978	12	29	23	1.4	3.6	2.7
Anhui	5333	7731	6440	52	51	52	5.1	4.0	4.4
Fujian	0	1918	885	0	18	12	0.0	1.0	0.6
Jiangxi	1384	2714	1998	29	33	31	1.3	1.4	1.4
Shandong	5835	19275	12038	29	44	39	5.6	9.9	8.3
Henan	6727	13837	10009	43	49	46	6.5	7.1	6.9
Hubei	4233	8659	6275	36	49	43	4.1	4.4	4.3
Hunan	3175	5684	4333	35	39	37	3.1	2.9	3.0
Guangdong	0	0	0	0	0	0	0.0	0.0	0.0
Guangxi	788	2744	1691	15	33	25	0.8	1.4	1.2
Hainan	72	802	409	8	41	30	0.1	0.4	0.3
Sichuan	7766	8905	8292	46	38	42	7.5	4.6	5.7
Guizhou	5377	10333	7664	75	79	77	5.2	5.3	5.3
Yunnan	1594	4560	2963	32	48	42	1.5	2.3	2.0
Shaanxi	3227	5749	4391	50	53	52	3.1	3.0	3.0
Gansu	3158	4298	3684	65	62	63	3.0	2.2	2.5
Qinghai	661	1212	915	59	62	61	0.6	0.6	0.6
Ningxia	1306	3900	2503	71	82	79	1.3	2.0	1.7
Xinjiang	3627	5437	4463	60	61	61	3.5	2.8	3.1
China	10982	20506	15378	38	42	41	100	100	100
# East	3028	6043	4420	26	30	29	32	34	33
# Middle	4628	8248	6299	44	51	48	36	34	35
# West	3326	6216	4660	53	58	56	32	32	32

Table 3
CO_2 marginal abatement cost by provinces and regions (Yuan/ton in 2005 price)

Provinces	Stage 1 1995-2001	Stage 2 2002-2007	Overall mean 1995-2007
Beijing	259.0	275.2	266.5
Tianjin	110.3	163.3	134.7
Hebei	86.2	16.8	54.2
Shanxi	30.0	32.3	31.1
Inner Mongolia	60.4	31.3	47.0
Liaoning	83.9	97.1	90.0
Jilin	75.9	100.2	87.1
Heilongjiang	83.6	125.4	102.9
Shanghai	127.1	197.3	159.5
Jiangsu	149.8	106.7	129.9
Zhejiang	168.6	167.6	168.1
Anhui	91.2	113.6	101.5
Fujian	269.3	218.2	245.7
Jiangxi	138.7	157.3	147.3
Shandong	137.2	26.5	86.1
Henan	110.3	43.7	79.5
Hubei	76.8	119.1	96.3
Hunan	131.2	148.5	139.2
Guangdong	190.7	214.4	201.7
Guangxi	92.0	158.5	122.7
Hainan	239.5	147.5	197.0
Sichuan	104.2	21.7	66.1
Guizhou	48.3	17.6	34.1
Yunnan	131.3	127.0	129.4
Shaanxi	97.0	110.1	103.1
Gansu	68.3	88.8	77.8
Qinghai	78.7	88.7	83.3
Ningxia	55.4	43.6	50.0
Xinjiang	77.8	94.6	85.6
China	116.3	112.2	114.4
# East	165.6	148.2	157.6
# Middle	92.2	105.0	98.1
# West	81.3	78.2	79.9

We construct the CO_2 ACI by taking into account both equity and efficiency principles.[9] The ACI is calculated by weighting the equity index and efficiency index as follows.

$$\boldsymbol{ACI}_{i,t} = \omega \times \boldsymbol{Equity}_{i,t} + (1-\omega) \times \boldsymbol{Efficiency}_{i,t}, \quad (10)$$

where $\boldsymbol{Equity}_{i,t}$ is the CO_2 abatement equity index for province i at period t and is combined with the per capita CO_2 emission and the per capita GDP, which are used to represent the equity criterion of "egalitarian" and "ability to pay[6, 8, 44, 45, 46]. The $\boldsymbol{Efficiency}_{i,t}$ is the CO_2 abatement efficiency index and consists of two components. The first component is the carbon intensity, the ratio of CO_2 emission to GDP. It is used to measure the emission benefit and productivity [7]. The second one is the CO_2 shadow price. It is employed to capture the marginal abatement cost.[10] All variables are normalized by the "Min-Max" method[11] and given the same weight when merged into equity and efficiency indexes.[12] The parameter $\boldsymbol{\omega}$ satisfies $0 \leq \omega \leq 1$ and reflects the policymakers' preferences between equity and efficiency principles.

We plot the average score of the equity index and efficiency index for 29 provinces from 1995 to 2007 in Figure 1. The dotted lines OA, OB and OC correspond to the same weight between equity and efficiency ($\omega = 1/2$), a preference for the efficiency principle ($\omega = 1/3$), and a preference for equity principles ($\omega = 2/3$).

[9] Chinese government has no detailed allocation plan for CO_2 intensity yet. The previous energy-saving plan is based on each province's proposal shown in the introduction.
[10] As equations (2) and (6) reveal, the CO_2 abatement potential and the shadow price are duals, following one reviewer's suggestion, we select the shadow price to be involved in the efficiency index.
[11] The "Min-Max" normalization method converts x_i to z_i by $z_i=(x_i-MinX)/(MaxX-MinX)$. The variable of the CO_2 shadow price is reverse transformed.
[12] For simplicity, we first assign the same weight to each variable when calculating the *Equity* and *Efficiency* indexes, later we will check if different weights affect the final results.

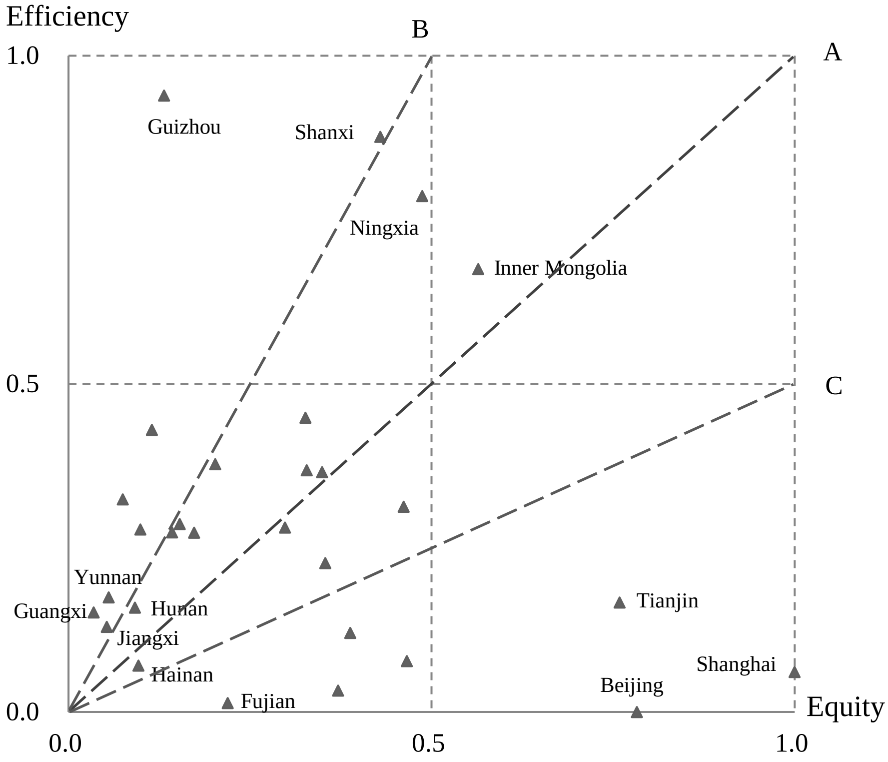

Figure 1 Distribution of Equity and Efficiency Indexes by Province (1995-2007)

The OA line shows there is no preference between equity and efficiency, and the points above (below) OA indicate that their efficiency score is higher (lower) than the equity index. Points far from the OA line indicate an asymmetric relationship between equity and efficiency performances. In addition, because the ACI index is combined with the equity and efficiency scores, each province's projected distance on line OA reflects its capacity to reduce CO_2. In this case, Shanxi gains the largest projected distance and the highest ACI score among all provinces, thus it should and can afford more abatement burden efficiently.

From Figure 1, we can observe that Inner Mongolia is located in the upper-right zone, meaning a high value of both *Equity* and *Efficiency* indexes. It is also far from the original point, thus achieving a higher ACI score when compared with other provinces. Most developed provinces, such as Beijing, Shanghai, and Tianjin, are scattered in the lower-right zone, showing that these provinces have higher *Equity* value but lower *Efficiency* value. In contrast, the upper-left zone, which includes Guizhou, Shanxi, and Ningxia, indicates that it will be more efficient in reducing CO_2 emissions in these regions. Moreover, we observe that in the lower-left zone, Hainan, Jiangxi, Guangxi, Yunnan, Hunan, and Fujian are close to the origin, which means that they have fewer responsibilities and abilities and are relatively less efficient in cutting CO_2 emissions.

The lines OB and OC reflect the policymakers' choices between efficiency and equity. If one favors the efficiency principle to allocate the CO_2 abatement task, those provinces with the highest projected distance on line OB, such as Shanxi, Ningxia, Guizhou, and Inner Mongolia, will be given high priority and a larger share of the CO_2 reduction burden. If the decision-maker prefers the equity principle, as line OC demonstrates, larger abatement shares will be distributed among regions such as Shanghai, Inner Mongolia, Ningxia, and Shanxi.

It is obvious that, under different choices between equity and efficiency principles, the outcome may vary greatly. Some extreme choices include the line OA rotating clockwise to the X axis and completely adopting the equity principle while ignoring allocation efficiency. In such a case, Shanghai ranks first and is able to afford more load than the other provinces.

We calculate the ACI score based on three assumed preference parameters (ω = 1/2, 2/3 and 1/3) and list the results in Table 4. Although the rankings of the provinces in Table 4 vary depending on different choices between equity and efficiency, some common provinces can be identified. Regardless, some provinces such as Inner Mongolia, Shanxi, and Ningxia should be allocated a larger burden share of the CO_2 abatement because of their high per capita emission and low abatement cost, but Shanghai should take on more burdens due to its high ability to pay and high per capita emission level. Contrarily, Jiangxi and Hainan can be distributed less loads because of their low emissions and high abatement costs, while Guangxi and Yunnan also can take on fewer burdens due to their low income levels and low emissions per capita.

Table 4
Average ACI score and rank by province in 1995-2007

Provinces	Equity		Efficiency		Equity and Efficiency are same important (ω=1/2)		Prior to Equity principle (ω=2/3)		Prior to Efficiency principle (ω=1/3)	
	Per capita CO_2	Per capita GDP	CO_2 intensity	CO_2 shadow price	ACI	Rank	ACI	Rank	ACI	Rank
Beijing	4.7	3.4	1.5	266.5	0.39	(7)	0.52	(6)	0.26	(15)
Tianjin	5.8	2.4	2.6	134.7	0.46	(6)	0.56	(5)	0.36	(7)
Hebei	3.6	1.1	3.6	54.2	0.39	(8)	0.37	(9)	0.41	(5)
Shanxi	4.8	0.9	5.6	31.1	0.65	(1)	0.58	(4)	0.73	(1)
Inner Mongolia	5.8	1.1	5.5	47.0	0.62	(3)	0.60	(2)	0.64	(4)
Liaoning	4.4	1.4	3.5	90.0	0.39	(9)	0.41	(7)	0.36	(8)
Jilin	3.7	1.0	4.0	87.1	0.35	(11)	0.34	(11)	0.35	(10)
Heilongjiang	3.3	1.1	3.4	102.9	0.29	(14)	0.29	(15)	0.29	(13)
Shanghai	6.1	3.9	1.7	159.5	0.53	(5)	0.69	(1)	0.37	(6)
Jiangsu	3.3	1.7	2.1	129.9	0.25	(17)	0.30	(14)	0.21	(21)
Zhejiang	3.7	2.0	1.9	168.1	0.27	(16)	0.34	(12)	0.21	(22)
Anhui	2.0	0.6	3.4	101.5	0.19	(23)	0.16	(22)	0.22	(20)
Fujian	2.2	1.4	1.6	245.7	0.12	(25)	0.15	(24)	0.08	(28)
Jiangxi	1.5	0.7	2.3	147.3	0.09	(28)	0.08	(28)	0.10	(27)
Shandong	3.4	1.4	2.5	86.1	0.29	(12)	0.31	(13)	0.27	(14)
Henan	2.3	0.8	2.9	79.5	0.22	(19)	0.20	(20)	0.24	(16)
Hubei	2.5	0.8	3.2	96.3	0.22	(18)	0.21	(19)	0.24	(18)
Hunan	1.8	0.7	2.6	139.2	0.13	(24)	0.11	(25)	0.14	(24)
Guangdong	2.9	1.9	1.6	201.7	0.20	(21)	0.26	(17)	0.15	(23)
Guangxi	1.4	0.6	2.3	122.7	0.09	(27)	0.07	(29)	0.11	(26)
Hainan	1.7	0.8	2.0	197.0	0.08	(29)	0.09	(27)	0.08	(29)
Sichuan	1.7	0.7	2.9	66.1	0.20	(22)	0.16	(23)	0.24	(17)
Guizhou	2.7	0.4	6.9	34.1	0.54	(4)	0.40	(8)	0.67	(3)
Yunnan	1.6	0.6	2.6	129.4	0.11	(26)	0.10	(26)	0.13	(25)
Shaanxi	2.3	0.7	3.3	103.1	0.21	(20)	0.19	(21)	0.23	(19)
Gansu	2.3	0.5	4.4	77.8	0.27	(15)	0.22	(18)	0.32	(11)
Qinghai	2.9	0.7	4.0	83.3	0.29	(13)	0.26	(16)	0.32	(12)
Ningxia	5.5	0.8	7.0	50.0	0.64	(2)	0.59	(3)	0.69	(2)
Xinjiang	3.9	1.0	4.0	85.6	0.36	(10)	0.35	(10)	0.36	(9)

Note: the unit of per capita CO_2, per capita GDP, CO_2 intensity and CO_2 shadow price is ton/person, 10000Yuan/person, ton/10000Yuan and Yuan/ton, respectively.

It is also apparent that the weight assigned to the component of *Equity* and *Efficiency* indexes will affect the final distribution. To examine the possible impact of component weight on the distribution, we drop the variable of CO_2 shadow price and CO_2 intensity from the *Efficiency* index and plot the distribution in Figure 2 and Figure 3, respectively. Compared with Figure 1, although the location of most provinces moved, their distribution among four blocks did not change greatly. Three developed provinces, Shanghai, Beijing, and Tianjin, are still located in the lower-right zone. Inner Mongolia, Shanxi, Ningxia, and Guizhou also remain situated in the upper block. However, Gansu and Hebei crossed the border slightly and moved into the upper-left zone in Figure 2 and Figure 3, respectively. If decision makers have no preference between equity and efficiency principles, both figures suggest that Inner Mongolia, Shanxi, Ningxia, Shanghai, Guizhou, and Tianjin will be given high priority to assume more burden because these provinces have a larger projected distance on line OA, thus a higher ACI score.[13]

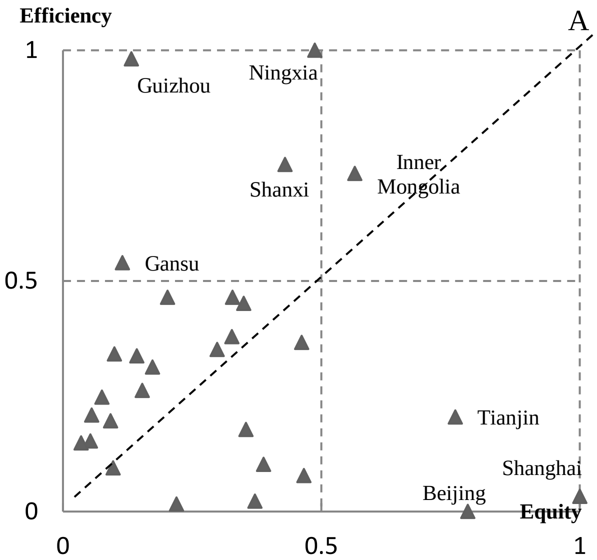

Figure 2 Distribution with two Equity components and one Efficiency component (CO_2 intensity)

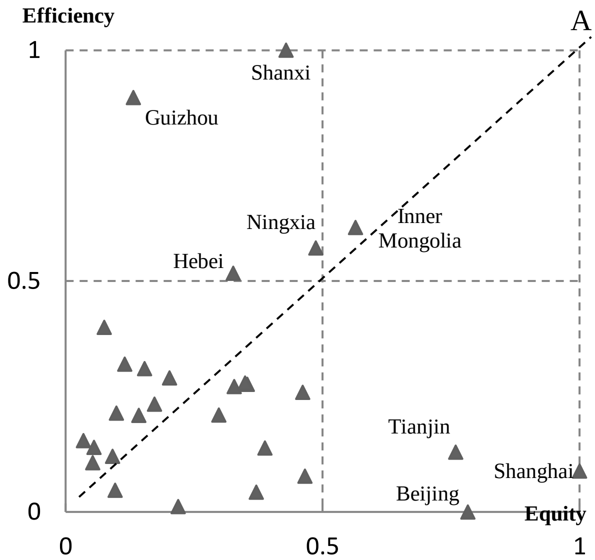

Figure 3 Distribution with two Equity components and one Efficiency component (shadow price)

We also check the impact of different composition of *Equity* index on the distribution. In Figures 4 and 5, we assign the whole weight 1 to per capita CO_2 and per capita GDP, respectively. In Figure 4, most provinces move toward the right when per capita GDP is ignored. Shanxi and Ningxia, which are located in the upper-left zone in Figure 1, now move to the upper-right zone. Xinjiang and Liaoning also move into the lower-right zone from the

[13] For those samples close to the original point, their ranks do not change significantly. Due to size limitation, we do not mark them in Figures 2 and 3, or in the following Figures 4 and 5.

lower-left zone. This new distribution means that these provinces--most are developing regions--will be allocated with more CO_2 abatement burden if the payment ability has not been taken into account. In Figure 5, most samples move toward the left when per capita CO_2 is dropped. Although Inner Mongolia moves to the upper-left zone from upper-right zone, its distribution among four blocks is similar to Figure 1. If the policymakers think equity is the same as the efficiency rule, both Figures 4 and 5 suggest that, Inner Mongolia, Ningxia, Shanxi, Guizhou, Tianjin, and Shanghai should be given a greater abatement share, although each province's ACI score and rank may vary.

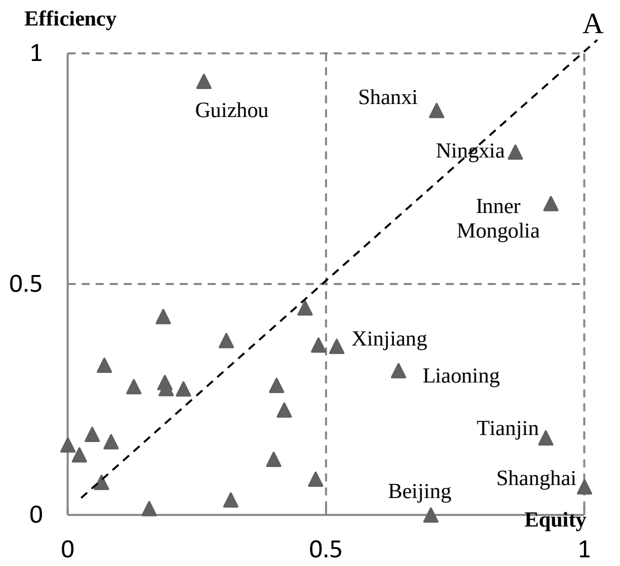

Figure 4 Distribution with one Equity component (per capita CO_2) and two Efficiency components

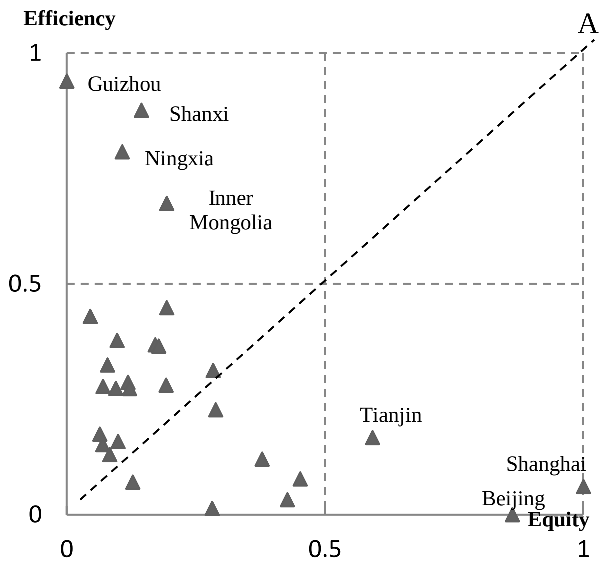

Figure 5 Distribution with one Equity component (per capita GDP) and two Efficiency components

There are several options for a final regional allocation scheme. Once the central governmental policymakers set up the proper components of *Equity* and *Efficiency* indexes, as well as the weigh coefficient between Equity and Efficiency, the provincial ACI score can be calculated. One may accurately distribute the CO_2 abatement volume target by relative ACI share in aggregated ACI, or classify these provinces by cluster analysis, for example, the average share burden can be set up equal to the national goal and the top five and the bottom five provinces will be allocated above-average and below-average targets.[14]

Furthermore, in addition to administrative policy and regulation, more market-based instruments can be developed to prompt efficiency improvement and emission abatement. Many studies and practices have proven that a tradable emission permit system is feasible and can achieve the goal efficiently [43, 14]. China is approaching this direction and has established several tradable emission permit markets, such as Beijing Environment Exchange, Shanghai Environment and Energy Exchange, and Tianjin Climate Exchange. Currently, most trade markets are for technology and property transfers. Some pollutants or CO_2-related transactions are voluntary exchanges, rather than the real market transactions that happened in the European Climate Exchange. In the next five years, China also plans to carry out pilot carbon trading in some industry sectors and provinces [2]. However, considering China's national strategy in international climate negotiation, the fact that China has yet to take on quantitative caps on emissions, the previous experience of implementing the energy-saving and emission-abatement goal during the 11th five-year plan, as well as the efficient decision-making and enforcement of the bureaucracy, there is no basis for carbon emission rights trading in China right now and it requires a certain length of time for China to trade carbon emission rights [47].

4.4 Determinants of CO_2 abatement potential

As shown in Table 2, great differences exist in CO_2 abatement potential, thus the inefficient emissions among provinces. To further investigate the driving force of CO_2 abatement potential, we conduct an econometric analysis as follows:

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[14] In the 11th five-year planning period, many provinces are allocated the same energy-saving target with national goal (20%), but Jilin (30%), Shanxi (25%), Inner Mongolia (25%) and Shandong (22%) undertake more burdens, while Hainan (12%), Guangxi (15%), Guangdong (16%), Fujian (16%), Yunnan (17%) and Qinghai (17%) afford less burdens. This practical distribution of energy-saving targets deviates from our ACI ranks as shown in Table 4, which were developed based on equity and efficiency considerations. These differences again reflect that allocation of energy-saving and emission-abatement in the 11th five-year plan was not systematically set and need to allocate target more scientifically in the 12th five-year plan [3, 5].

$$AP_{i,t} = \beta_0 + \beta_1 ln(rGDP)_{i,t} + \beta_2 Heavy_{i,t} + \beta_3 Service + \beta_4 Coal_{i,t}$$
$$+\beta_5 Trade_{i,t} + \beta_6 D2002 + \varepsilon_{i,t,} \quad (11)$$

where $AP_{i,t}$ is the CO_2 abatement potential (inefficient emission) for the *i*–th province at year *t*. β_0 is a constant item and $\varepsilon_{i,t}$ is an error term. The independent variables *ln(rGDP)*, *Heavy*, *Service*, *Coal* and *Trade* denote the initial income levels, the share of the heavy industry sector in the economy, the share of tertiary industry share in GDP, the share of coal in total energy and the share of international trade in GDP, respectively. The dummy variable *D2002* is used to check if year 2002 is a turning point.

The most developed regions, such as Beijing and Shanghai, register a lower CO_2 abatement potential, while the less developed regions have higher *AP* values (Table 2). Because the abatement potential of CO_2 reflects the inefficient emission of CO_2 during the production process, it is expected that the richer provinces, which are normally accompanied by higher economic efficiency, have less inefficient emissions and lower CO_2 abatement potential. Here we use the per capita GDP to represent the initial income levels (in logarithm form).

Some studies found that industrial structure change exerts great influence on energy efficiency [48, 49]. A shift from the high-energy-consumption sectors to the low-energy-consumption sectors can increase total energy efficiency, which may lead to less CO_2 abatement potential. We use the ratio of the heavy industry sector to GDP and the share of the tertiary industry in GDP to indicate each province's industry structure. We expect that the coefficients of the heavy industry share and the tertiary industry share are positive and negative, respectively.

Because various energy products have different carbon contents, energy composition should be taken into account as an important factor [50]. In order to control for potential provincial varying trends in fuel mix, we follow Auffhammer and Carson's [51] method to use the share of coal in total energy consumption to proxy the energy consumption structure.[15] The data of coal and total energy consumptions are taken from *China Energy Statistical Yearbook* [38]. Because the carbon content of coal is higher than other non-coal energy products, the coefficients of *Coal* are expected to be positive.

As Taskin and Zaim [52] revealed, the openness of a country is one of the key determinants of environmental efficiency. In the last three decades, China's open-door policy has substantially increased imports and exports. To capture the effect of openness on CO_2 abatement potential, we use the share of imports and exports in the total economy to represent the openness levels for each province. It can also be used to proxy the institution change [53]. The sign of the variable *Trade* is expected to be negative.

Considering that the CO_2 abatement potential value is between 0 and 1, a Tobit estimation on Equation (11) is employed [28]. To avoid potential problems caused by unobserved variables, we apply the generalized least squares (GLS). The Hausman-test prefers the fixed-effect (FE) model. Table 5 lists the results of the Tobit regression with year controlled and the two-way FE estimation results.

As expected, the sign of the variable *ln(rGDP)* is negative, but the coefficients are insignificant in all estimators. It suggests that there is no remarkable connection between the economic development level and the CO_2 abatement potential.

The sign of the variable *Heavy* is consistent with our expectations. The remarkable positive coefficient suggests that a greater share of the heavy industry sector in the economy leads to more inefficient CO_2 emissions. On the contrary, the significantly negative coefficient of the variable *Service* indicates that a greater share of tertiary industry in GDP leads to a lower CO_2 abatement potential.

[15] More importantly, it is better to add the share of renewable energy to capture the differences between fossil fuel and renewable energy, but the data of renewable energy consumption for each province is not available.

Table 5
Regression results of CO_2 abatement potential

Independent variables	Tobit	FE
Per capita GDP ***ln(rGDP)***	-0.076 (0.059)	-0.104 (0.104)
Heavy industry share ***Heavy***	0.648 *** (0.135)	0.401 *** (0.154)
Tertiary industry share ***Service***	-0.743 *** (0.269)	-0.607** (0.256)
Coal share ***Coal***	0.610 *** (0.116)	0.683 *** (0.118)
International trade share ***Trade***	-0.167 *** (0.065)	-0.074 * (0.044)
Year Dummy ***D2002***	0.14 *** (0.05)	0.17 ** (0.076)
Constant item	-0.143 (0.142)	-0.098 (0.147)
Observations	315	371
Log likelihood	221.5	
Adj. R^2		0.591

Notes: ***, ** and * denote that the variables are statistically significant at the 1, 5 and 10 percent levels, respectively. Standard errors are reported in parentheses.

The energy composition, represented by the share of coal in total energy consumption, is consistent with our expectations in the whole sample. This indicates that the composition of energy consumption plays an important role in the fluctuation of provincial CO_2 abatement potential. The significant positive coefficient of *Coal* suggests that the inefficiency of CO_2 emission will raise the increasing consumption of more coal energy mixes.

The *Trade* variable is notably correlated with the CO_2 abatement potential. Its negative coefficient reveals that greater trade openness leads to more efficient CO_2 emissions. In addition, the significantly positive coefficient of the dummy variable *D2002* verifies that the CO_2 abatement potential has significantly increased since 2002.

According to the magnitude of coefficients, coal share in total energy consumption, tertiary industry share and heavy industry share contribute to the majority of abatement potential's variety, while trade openness contributes relatively less. In other words, the industry composition and the energy mix play relatively important roles on the change in CO_2 abatement potential.

In summary, the large gap of CO_2 abatement potential among provinces may result from different industry structures, energy compositions, and degrees of openness. A greater share of the heavy industry sector and more consumption of coal energy mixes in the economy leads to more inefficient CO_2 emissions. The more the service sector develops and the more open trade is, the more efficient CO_2 emissions will be.

5. Conclusion

China has committed to reducing its carbon intensity by 40-45% below 2005 levels by 2020. The economic reform in the past 30 years has allowed free market to take on more roles in economic development. However, government still intervenes in the economics directly, especially in the energy sector. Under this setting, we predict that government will still make a key role in allocating CO_2 abatement. The purpose of the paper tries to propose how to equitably and efficiently distribute this national goal to each province. We identify some provinces with the highest (lowest) capacity to reduce CO_2 from both equity and efficiency perspectives. We apply the "common but differentiated responsibilities" rule, which is used in international negotiation and the allocation of CO_2 permits across nations, to regional distribution in China.

By taking undesirable output into account, an extended SBM DEA model is employed to measure redundant CO_2 emissions using data from 29 provinces in China over the period 1995-2007. The estimated provincial CO_2 marginal abatement costs, combined with carbon intensity, are merged into the CO_2 abatement efficiency index. The CO_2 abatement equity index is defined by per capita CO_2 and per capita GDP. Then, the CO_2 ACI is constructed by the weighted CO_2 abatement efficiency index and the CO_2 abatement equity index.

The ACI ranks may vary and it depends on the decision makers' preferences between equity and efficiency principles, as well as the components of *Equity* and *Efficiency* indexes. By setting different parameters in three scenarios, the results suggest that Inner Mongolia, Shanxi, Ningxia and Shanghai should increase their loads, while Jiangxi, Guangxi, Hainan, and Yunnan should have their loads reduced. However, an interregional tradable emission permit system can help obtain both equity and efficiency objectives in the future.

There exists a large reduction potential gap between the eastern, the middle and the western regions. The emission abatement potential (inefficient emission) in the eastern region is 29%, while it is 48% and 56% in the middle and western regions, respectively. On average, 41% national CO_2 emissions are excessive due to inefficient production (equivalent to 153.78 million tons per year). The east, middle and west regions contributed 33%, 35% and 32%, respectively, of the national feasible abatement during this period. Our regression results indicate that the large gap of CO_2 abatement potential among provinces may result from different industry structures, energy compositions and degrees of openness. In addition, the distribution of marginal cost across regions and over time is unbalanced. The national marginal abatement cost climbed from 94.4 Yuan/ton in 1995 to 139.5 Yuan/ton in 2002 and then continuously declined. The developed eastern region (157.6 Yuan/ton) shows the highest marginal cost to reduce CO_2, while the average shadow prices in the middle and western regions are 98.1 Yuan/ton and 79.9 Yuan/ton, respectively.

Finally, we have to admit the limitation of applying DEA models to province levels in China. DEA models have a strong assumption of homogeneity among the decision-making units [54]. They are most frequently used in analyzing productive efficiency of firms and organizations**.** We apply DEA to provincial level analysis following the other literature in regional/industrial studies [28, 55, 56] and the research among countries [29, 35, 57, 58, 59, 60]. However, each province is different in the availability of technology and labor mobility. Our regression in Section 4 further examines the provincial difference of CO_2 abatement potential. In the future research, we will pursue a better solution to fit the homogenous assumption of the DEA model.

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