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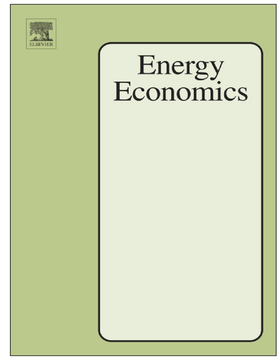


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# Performance Evaluation of Organizations Considering Economic Incentives for Emission Reduction: A Carbon Emission Permit Trading Approach

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**Abstract**

The emissions trading system allows organizations to transact emission permits to fit their production practice. This paper develops a new nonparametric methodology for performance evaluation of organizations (or decision-making units, DMUs) considering carbon emission permit trading. Explicit production axioms are discussed, and a new production technology considering carbon emission permit trading is proposed. Models based on the new production technology are established for evaluating the carbon emission reduction potential and performance of the DMUs. Comparing the proposed models with previous ones, the adoption of carbon emission permit trading increases the potentials of DMUs to reduce carbon dioxide emission and improve inputs and outputs. In addition, a proper increase of the carbon emission permit trading price can increase the potential of DMUs to reduce carbon dioxide emissions. The proposed approach contributes to the literature by explicitly explaining how adopting carbon emission permit trading affects production technology. A numeral example illustrates the proposed approach while the usefulness and practicality of the models are explained by applying them to China's thermal power industry.

*Keywords:* Data envelopment analysis, carbon emission permit trading, production technology, efficiency evaluation, abatement potential

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## 1. Introduction

Human beings have increasingly influenced the global climate. Human activities are continuously adding enormous amounts of greenhouse gases to the atmosphere, which increases the greenhouse effect and causes man-induced climate change. The planet is warming up considerably faster now than ever in recent millions of years. The Intergovernmental Panel on Climate Change (IPCC) Special Report "Global Warming of 1.5 °C" (2018) clearly states that carbon dioxide is the main driver of long-term global warming. The Paris Agreement was signed to slow down the pace of global warming, and some of the parties submitted substantial commitments regarding their carbon dioxide emission reduction plans. For instance, China, as the world's largest carbon dioxide emitter, committed to a 60%–65% reduction in its carbon dioxide emission at the end of the year 2030 compared with that in 2005.

Some Paris Agreement signatories (e.g., the European Union (EU), China, Canada, and Australia) also adopted the emissions trading system (ETS), which provides economic incentives for emission reduction, to realize carbon dioxide abatement. ETS usually operates under the "cap and trade" principle. The "cap" denotes the total amount of allowable greenhouse gas emission, while the "trade" indicates that the companies are permitted to trade their emission allowances with one another. Although some signatories have proposed specific carbon dioxide emission reduction plans, it is essential to introduce appropriate methods to investigate the environmental efficiency of the organizations and determine their carbon dioxide emission reduction potentials. More importantly, the effects of emission trading mechanisms on the production technology and the emission reduction potential of the organizations must also be investigated. In DEA, the production technology is also known as the production possibility set. It is the set of the possible productions of the DMUs mathematically formulated by the production data of observed DMUs (Banker et al. 1984; Chu and Zhu 2021). The formulation of the conventional production technology requires the use of some standard production axioms. When emission trading is adopted, some standard axioms (e.g., weak-disposability and cone-convexity) need to be reformulated. Therefore, the mathematical formulation of the production technology needs to be adjusted accordingly. Specifically, more possible productions of the DMUs, formulated because of the existence of the emission trading, need to be added to the production technology (or production possibility set).

Data envelopment analysis (DEA) (Charnes et al. 1978), a data-driven and nonparametric method, has been widely adopted for efficiency evaluation of organizations (called decision-making units, DMUs) with multiple inputs and outputs. DEA evaluates and produces production targets for the DMU by comparing its production with the productions on the technical (or efficient) frontier, which is constructed using the production data of all the DMUs. The carbon dioxide emission of the DMU is regarded as an undesirable output (environment factors) in DEA and thus should be minimized. By contrast, DEA outputs are traditionally desirable and should be maximized. The main technical difficulty in DEA-based carbon emission efficiency evaluation is the modeling of undesirable outputs. To handle this problem, scholars have proposed several methods, such as considering undesirable outputs as inputs (Seiford and Zhu 2002, 2005; Amirteimoori et al. 2006), using data transformations (Ali and Seiford 1990; Hua et al. 2007), modeling with the directional distance function (Chung et al. 1997; Chen and Delmas 2012), and assuming weak disposability (Färe et al. 1989; Färe and Grosskopf 2003, 2004; Hailu and Veeman, 2001; Hailu 2003; Kuosmanen 2005; Kuosmanen and Podinovski 2009). A critical review regarding these methods can be found in Halkos and Petrou (2019). Based on the above methods of handling undesirable outputs, scholars introduced numerous models for carbon emission performance evaluation of China's provincial regions (Guo et al. 2011; Wang et al. 2012; Bian et al. 2013; Zha et al. 2016; Meng et al. 2016; Miao et al. 2019; Zhang et al. 2019; Yang et al. 2020; Miao et al. 2021), OECD countries (Zaim and Taskin 2000; Zhou et al. 2007; Guo et al. 2017), belt and road countries (Liu and Xin 2019; Wang et al. 2021), transport and industrial sectors (Zhou et al. 2013; Stefaniec et al. 2020), and thermal power industry (Sueyoshi et al. 2010; Bi et al. 2014; Hampf and Rødseth 2015; Wang et al. 2019; Zhu et al. 2020; Zhu et al. 2021).

The existing studies only regarded carbon dioxide emission as an undesirable output and built the production possibility set for efficiency evaluation. However, none of the existing studies noted that the adoption of the carbon emission trading mechanism leads to alterations when building the production possibility set (or production technology). Specifically, when conducting production axiom analysis for the production technology, the production of a DMU is assumed to belong to the production technology with a variation on its carbon dioxide emission. If the carbon emission trading mechanism is adopted, then such a variation would require trading of carbon emission permits in ETS to fit the DMU's changed amount of carbon dioxide emission, which results in an additional change of its monetary output. However, in the existing production axiom analysis, this trading between the carbon emission permits and the monetary output has not been considered, leading to the problem that the production technologies built by previous studies do not include new generated DMUs whose monetary output has been additionally increased or decreased. Therefore, if emission trading is adopted, the traditional production axioms may fail to reflect practice accurately. Thus, the production technology must be reinvestigated.

This paper develops a new methodology for the performance evaluation of DMUs considering carbon emission permit trading to fill the research gap just explained. Explicit production axioms are provided considering carbon emission permit trading. A new production technology is also built. Furthermore, several models are proposed to estimate the reduction potential of carbon dioxide emission and evaluate DMU efficiency. Additionally, the effects of the carbon emission trading mechanism on the reduction potential of carbon dioxide emission and the DMU efficiencies are analyzed. This study contributes to the literature by providing a novel nonparametric production technology considering carbon emission trading and analyzing the influence mechanism of carbon emission trading. Finally, the proposed approach is applied to a case study of China's thermal power industry.

The remainder of this paper is organized as follows. Section 2 discusses the production technology. Section 3 proposes models for carbon emission abatement potential estimation and performance evaluation of the DMUs. Section 4 uses an illustrative example for model comparison and sensitivity analysis. Section 5 provides a case study of the thermal power industry of China. Section 6 finally provides the conclusions and future research perspectives.

## 2. Production Technology

The standard production axioms are introduced in this section, and a new axiom of interval proportionality considering emission trading is proposed. The production possibility set considering carbon emission permit trading is also provided. First, the following notation, which is used throughout the paper, is provided.

General parameters: $n$: Number of DMUs; $m$: Number of inputs; $s$: Number of desirable outputs.

Data parameters: $x_{ij}$: $i^{th}$ $(i \in I = \{1, \dots, m\})$ input of DMU $j$ $(j \in J = \{1, \dots, n\})$; $y_{rj}$: $r^{th}$ $(r \in O = \{1, \dots, s\})$ desirable output of DMU $j$ $(j \in J)$; $g_j$: Monetary products of DMU $j$ $(j \in J)$; $b_j$: Carbon dioxide of DMU $j$ $(j \in J)$; $c$: Trading price of carbon emission permit.

Decision variables: $\lambda_j$: Intensity variable attached to DMU $j$ $(j \in J)$.

The inputs and desirable outputs of DMU $j$ $(j \in J)$ form the vectors $X_j$ and $Y_j$, respectively, that is, $X_j = \left(x_{1j}, \dots, x_{mj}\right)^T$ and $Y_j = \left(y_{1j}, \dots, y_{sj}\right)^T$. The situation where $n$ DMUs must be evaluated is considered. Each DMU uses $m$ inputs to produce $s$ desirable outputs, one monetary output, and carbon dioxide. Notably, the monetary output is also a desirable output of the DMU. The detailed production structure of the DMU is shown in Figure 1.

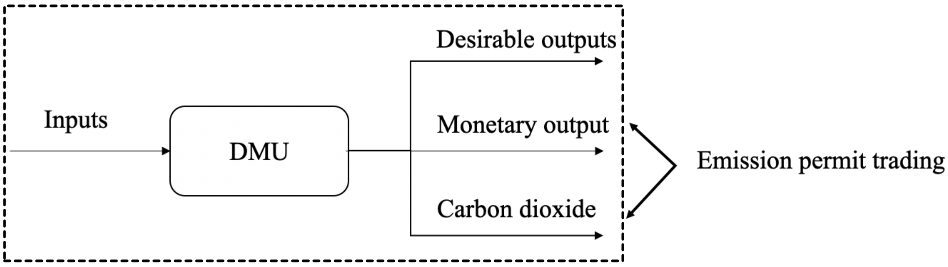


**Figure 1**. Production structure of the DMU

The production process of the DMU is shown in the dashed box of Figure 1. It can be seen that some inputs are used in each DMU to produce desirable outputs, monetary output, and carbon dioxide. When emission permit trading is considered, a DMU may trade in the market to buy or sell some amount of emission permit to fit its emission of carbon dioxide; the emission permit transactions can change its monetary output. This is also the main motivation of our study.

*2.1 Standard Axioms*

$T=\{(X,Y,g,b)|X\ can\ produce\ Y,g\ and\ b\}\in\mathbb{R}_{+}^{m+s+2}$ denotes the production possibility set of the DMUs. $T$ is assumed to satisfy the following conventional production axioms. An additional axiom considering the carbon emission permit trading will be discussed in Section 2.2.

**Axiom 1.** *Feasibility*: All the observed DMUs belong to $T$, that is, $(X_j,Y_j,g_j,b_j)\in T,\forall j\in J$.

**Axiom 2.** *Convexity*: $(X_j,Y_j,g_j,b_j)\in T$ implies that $\left(\sum_{j=1}^{n}u_jX_j,\sum_{j=1}^{n}u_jY_j,\sum_{j=1}^{n}u_jg_j,\sum_{j=1}^{n}u_jb_j\right)\in T$, where $\sum_{j=1}^{n}u_j=1$ and $u_j\geq 0,\forall j\in J$.

**Axiom 3.** *Free disposability of input and desirable output*: $(X,Y,g,b)\in T$, $X'\geq X$, $Y'\leq Y$, $g'\leq g$, and $b'=b$ imply that $(X',Y',g',b')\in T$.

**Axiom 4.** *Weak disposability of the undesirable output*: $(X,Y,g,b)\in T$ and $0\leq\alpha\leq 1$ imply that $(X,\alpha Y,\alpha g,\alpha b)\in T$.

Färe et al. (1989) proposed Axiom 4, which was later discussed by Hailu and Veeman (2001), Färe and Grosskopf (2003), Hailu (2003), and Kousmanen (2005). This axiom indicates that with a given level of input resource, the reduction of undesirable output ($b$) in the production requires the reduction of desirable outputs ($Y$ and $g$) simultaneously. For instance, a 10% reduction in carbon dioxide emission is possible for a DMU if accompanied by a 10% reduction in its desirable and monetary outputs, while keeping the inputs of this DMU constant. This assumption is consistent with the production practice and has been widely applied in various studies (e.g., Chen and Delmas 2012, Kousmanen and Matin 2011, Podinovski and Kuosmanen 2011, Mehdiloo and Podinovski, 2019).

*2.2 Production axiom considering carbon emission permit trading*

A new axiom considering carbon emission permit trading is discussed in this section. The following Assumption 1 is first provided.

**Assumption 1.** The carbon dioxide emission permit possessed by a DMU is assumed to be equal to the emitted carbon dioxide amount.

Based on Assumption 1, if a DMU is required to emit less carbon dioxide than its permit allows, then the DMU must trade in the emission trading system to obtain a carbon emission permit consistent with the emission amount. As can be seen in the above analysis of the production axioms, we assume some possible productions of DMUs based on the practical production situations of the observed DMUs. That is, the production data of the DMUs in the past is used as the basis for the production axiom analysis. Because the DMU produces a certain amount of carbon dioxide in a production period, it must possess and use the same amount of emission permit to support its production. So, for example, when we assume a new production of a DMU reduces its carbon emission, it would retain some amount of unused emission permit that will be sold in the market to generate additional monetary output. Therefore, in

Assumption 1, we assume that the emission permit possessed by a DMU is equal to its emitted carbon dioxide amount when adopting emission trading. For example, if a thermal power plant emitted $1.0 \times 10^8$ tons of carbon dioxide in a production period, then it should possess and use $1.0 \times 10^8$ tons of carbon emission permit. Additionally, if the company's production is changed and its emission of carbon dioxide reduces to $0.8 \times 10^8$ tons, then it would remain $0.2 \times 10^8$ tons of unused emission permit which could be sold in the market to generate additional revenue for it.

Axiom 4 indicates that with the given input level, a DMU can produce an output level that is a proportional reduction of the current level. However, this axiom fails to reflect the practical situation when the carbon emission permit trading is considered. Specifically, the following case can be considered.

**Case 1.** Based on Axiom 4, if $(X, Y, g, b) \in T$, then $(X, \alpha Y, \alpha g, \alpha b) \in T$, where $0 \leq \alpha \leq 1$. This condition indicates that the DMU can produce the output level $(\alpha Y, \alpha g, \alpha b)$ with the given input level $X$. Therefore, the carbon emission permit of this DMU should be reduced to $\alpha b$ to fit the emission practice. Specifically, according to Assumption 1, the DMU possesses the carbon emission permit of $b$, which is more than the amount of its carbon dioxide production. Thus, the DMU would sell the exceeded carbon emission permit (i.e., $(1-\alpha)b$), resulting in changing the monetary output to $\alpha g + c(1-\alpha)b$.

Based on the above analysis, a new Axiom 4* is presented as follows.

**Axiom 4*.** *Weak disposability of the undesirable output considering emission trading*: $(X, Y, g, b) \in T$ and $0 \leq \alpha \leq 1$ imply that $(X, \alpha Y, \alpha g + c(1-\alpha)b, \alpha b) \in T$.

**Remark 1.** Axiom 4* considers not only the weak disposability assumption of the undesirable output but also regards the DMU's trading of its excess carbon emission permit, which increases its monetary output.

*2.3 Production possibility sets*

A production possibility sets (PPS) with and without the carbon emission permit trading is defined using the minimum extrapolation principle. This principle defines the PPS as the minimum set containing all possible productions discussed in the production axioms (Banker et al. 1984). The PPS is the smallest possible, so it does not contain any arbitrary or redundant productions.

**Definition 1.** When carbon emission permit trading is not considered, technology $T^{NTRD} = (X, Y, g, b) \in \mathbb{R}_{+}^{m+s+2}$ is the intersection of all the productions satisfying Axioms 1–4.

Kuosmanen (2005) indicated that $T^{NTRD}$ is the set of all DMUs $(X, Y, g, b) \in \mathbb{R}_{+}^{m+s+2}$ from which $\lambda_j \geq 0, \forall j \in J$ and $\mu_j \geq 0, \forall j \in J$ exist such that the following conditions are true:

$$\sum_{j=1}^{n} (\lambda_j + \mu_j) X_j \leq X \quad (1a)$$

$$\sum_{j=1}^{n} \lambda_j Y_j \geq Y, \quad (1b)$$

$$\sum_{j=1}^{n} \lambda_j g_j \geq g, \quad (1c)$$

$$\sum_{j=1}^{n} \lambda_j b_j = b \quad (1d)$$

$$\sum_{j=1}^{n} (\lambda_j + \mu_j) = 1, \quad (1e)$$

$$\lambda_j \geq 0 \qquad \forall j \in J, \quad (1f)$$

$$\mu_j \geq 0 \qquad \forall j \in J. \quad (1g)$$

**Definition 2.** When carbon emission permit trading is considered, technology $T^{TRD} = (X, Y, g, b) \in \mathbb{R}_{+}^{m+s+2}$ is the intersection of all the productions satisfying Axioms 1, 2, 3, and 4*.

**Theorem 1.** *Technology* $T^{TRD}$ *is the set of all DMUs* $(X, Y, g, b) \in \mathbb{R}_{+}^{m+s+2}$ *from which* $\lambda_j \geq 0, \forall j \in J$ *and* $\mu_j \geq 0, \forall j \in J$ *exist such that the following conditions are true:*

$$\sum_{j=1}^{n} (\lambda_j + \mu_j) X_j \leq X, \quad (2a)$$

$$\sum_{j=1}^{n} \lambda_j Y_j \geq Y, \quad (2b)$$

$$\sum_{j=1}^{n} (\lambda_j g_j + c\mu_j b_j) \geq g, \quad (2c)$$

$$\sum_{j=1}^{n} \lambda_j b_j = b, \quad (2d)$$

$$\sum_{j=1}^{n}(\lambda_j + \mu_j) = 1, \tag{2e}$$

$$\lambda_j \geq 0 \qquad \forall j \in J, \tag{2f}$$

$$\mu_j \geq 0 \qquad \forall j \in J. \tag{2g}$$

**Proof.** According to Axioms 1–3 and 4*, if $(X, Y, g, b) \in \mathbb{R}_{+}^{m+s+2}$ contains all the productions satisfying these axioms, then the following conditions should be satisfied.

$$\sum_{j=1}^{n} u_j X_j \leq X, \tag{3a}$$

$$\sum_{j=1}^{n} u_j \alpha_j Y_j \geq Y, \tag{3b}$$

$$\sum_{j=1}^{n} u_j\left[\alpha_j g_j + c(1-\alpha_j) b_j\right] \geq g, \tag{3c}$$

$$\sum_{j=1}^{n} u_j \alpha_j b_j = b, \tag{3d}$$

$$\sum_{j=1}^{n} u_j = 1, \tag{3e}$$

$$u_j \geq 0 \qquad \forall j \in J, \tag{3f}$$

$$0 \leq \alpha_j \leq 1 \qquad \forall j \in J. \tag{3g}$$

Let $\varphi_j = 1 - \alpha_j, \forall j \in J$. $\varphi_j \geq 0, \forall j \in J$ because $0 \leq \alpha_j \leq 1$. Then, the above formulations can be transformed into the following (4).

$$\sum_{j=1}^{n} u_j(\alpha_j + \varphi_j) X_j \leq X, \tag{4a}$$

$$\sum_{j=1}^{n} u_j \alpha_j Y_j \geq Y, \tag{4b}$$

$$\sum_{j=1}^{n} u_j \alpha_j g_j + c u_j \varphi_j b_j \geq g, \tag{4c}$$

$$\sum_{j=1}^{n} u_j \alpha_j b_j = b, \tag{4d}$$

$$\sum_{j=1}^{n} u_j\,(\alpha_j + \varphi_j) = 1, \tag{4e}$$

$$u_j \geq 0 \qquad \forall j \in J, \tag{4f}$$

$$0 \leq \alpha_j \leq 1 \qquad \forall j \in J, \tag{4g}$$

$$\varphi_j \geq 0 \qquad \forall j \in J. \tag{4h}$$

Let $\lambda_j = u_j \alpha_j$ and $\mu_j = u_j \varphi_j$. Then, the mathematical formulation of Technology $T^{TRD}$ can be presented as the equations in (2). Q.E.D.

**Theorem 2.** $(X, Y, g, b) \in T^{NTRD}$ implies $(X, Y, g, b) \in T^{TRD}$.

**Proof.** $(X, Y, g, b) \in T^{NTRD}$ indicates the existence of $\lambda_j \geq 0, \forall j \in J$ and $\mu_j \geq 0, \forall j \in J$ such that the conditions in (2) are true. Comparing (2) and (1), only constraints $\sum_{j=1}^{n} \lambda_j g_j \geq g$ (1c) and $\sum_{j=1}^{n}(\lambda_j g_j + c\mu_j b_j) \geq g$ (2c) are different. (1c) implies (2c) because $\mu_j \geq 0, \forall j \in J$, $c \geq 0$, and $b_j \geq 0, \forall j \in J$. Therefore, $\lambda_j \geq 0, \forall j \in J$ *and* $\mu_j \geq 0, \forall j \in J$ exist such that the conditions in (1) hold and $(X, Y, g, b) \in T^{TRD}$. Q.E.D.

**Remark 2.** Theorem 2 states that $T^{NTRD}$ is a subset of $T^{TRD}$. This statement means that the production technology $T^{TRD}$ can perform all the productions in $T^{NTRD}$ after adopting the carbon emission permit mechanism. This theorem also indicates that adopting the carbon emission permit trading mechanism does not deteriorate the production technology of the DMUs. Therefore, the DMUs gain additional potential to improve their productions (this point will be further discussed in Section 3).

**Remark 3.** Technology $T^{TRD}$ uses the variable returns to scale (VRS) assumption. The constant returns to scale (CRS) assumption can be considered by adopting the cone-convexity axiom (Charnes et al. 1978; Podinovski et al. 2017), which indicates that a proportional scaling of a DMU production also belongs to the PPS. However, the conventional cone-convexity axiom fails to reflect the practical situation when considering carbon emission permit trading. Thus, this axiom must be changed similarly to that indicated for Axiom 4. Detailed discussions regarding the CRS production technology considering carbon emission permit trading are provided in Appendix A.

## 3. Methodology and Models

The models used to investigate the potential of DMUs in reducing carbon dioxide emission are proposed in this section. Then, models for the efficiency evaluation of the DMUs considering the improvements of all their inputs and outputs are introduced.

*3.1 Potential of carbon dioxide emission abatement*

The main idea of carbon emission abatement potential estimation is to compare the DMU's production with the productions in the PPS to determine the amount of its carbon dioxide reduction while maintaining its levels of the other inputs and outputs. The carbon emission abatement potential shows the capability of DMUs in reducing carbon dioxide emissions considering improved production technology to facilitate efficient production. When carbon emission permit trading is not considered, $T^{NTRD}$ is adopted, and the following Model (5) is used for the estimation considering DMU $d$ ($\forall d \in J$). This model has also been used in Kuosmanen et al. (2005), Kuosmanen and Podinovski (2009), and Lee (2018).

$$\Delta b_d^{NTRD} = \max \Delta b_d, \tag{5}$$

$$\text{Subject to} \quad \sum_{j=1}^{n} (\lambda_j + \mu_j) X_j \leq X_d, \tag{5a}$$

$$\sum_{j=1}^{n} \lambda_j Y_j \geq Y_d, \tag{5b}$$

$$\sum_{j=1}^{n} \lambda_j g_j \geq g_d, \tag{5c}$$

$$\sum_{j=1}^{n} \lambda_j b_j = b_d - \Delta b_d, \tag{5d}$$

$$\sum_{j=1}^{n} (\lambda_j + \mu_j) = 1, \tag{5e}$$

$$\lambda_j \geq 0 \quad \forall j \in J, \tag{5f}$$

$$\mu_j \geq 0 \quad \forall j \in J, \tag{5g}$$

$$\Delta b_d \geq 0. \tag{5h}$$

Similarly, $T^{TRD}$ can be used when considering carbon emission permit trading, and the following Model (6) can be adopted to estimate the carbon emission abatement potential for DMU $d$ ($\forall d \in J$).

$$\Delta b_d^{TRD} = \max \Delta b_d, \tag{6}$$

$$\text{Subject to} \quad \sum_{j=1}^{n} (\lambda_j + \mu_j) X_j \leq X_d, \tag{6a}$$

$$\sum_{j=1}^{n} \lambda_j Y_j \geq Y_d, \tag{6b}$$

$$\sum_{j=1}^{n} (\lambda_j g_j + c\mu_j b_j) \geq g_d, \tag{6c}$$

$$\sum_{j=1}^{n} \lambda_j b_j = b_d - \Delta b_d, \tag{6d}$$

$$\sum_{j=1}^{n} \left(\lambda_j + \mu_j\right) = 1, \tag{6e}$$

$$\lambda_j \geq 0 \qquad \forall j \in J, \tag{6f}$$

$$\mu_j \geq 0 \qquad \forall j \in J, \tag{6g}$$

$$\Delta b_d \geq 0. \tag{6h}$$

The carbon dioxide emission abatement potentials ($\Delta b_d^{NTRD}$ and $\Delta b_d^{TRD}$) of DMU $d$ are assessed by solving Models (5) and (6) using production technologies without and with carbon emission permit trading, respectively.

**Proposition 1.** $\Delta b_d^{NTRD} \leq \Delta b_d^{TRD}, \forall d \in J$.

**Proof.** The proof of Theorem 1 can be used to easily verify that a feasible solution of Model (5) is always a feasible solution of Model (6). Therefore, $\Delta b_d^{NTRD} \leq \Delta b_d^{TRD}$. Q.E.D.

**Theorem 3.** Regarding the optimal objective function value $\Delta b_d^{TRD}(c)$ of Model (6) as a function of the trading price $c$ of carbon emission permit, $\Delta b_d^{TRD}(c)$ is monotonic non-decreasing with the increasing of $c$.

**Proof.** Let $0 \leq c' \leq c''$. Model (6) is solved with $c = c'$, and the optimal solution $\left(\lambda_j', \forall j \in J, \mu_j', \forall j \in J, \Delta b_d'\right)$ is obtained. Thus, $\Delta b_d^{TRD}(c') = \Delta b_d'$. $\sum_{j=1}^{n}\left(\lambda_j' g_j + c' \mu_j' b_j\right) \geq g_d$ due to the constraint (6c). $\sum_{j=1}^{n}\left(\lambda_j' g_j + c'' \mu_j' b_j\right) \geq g_d$ because $c'' \geq c' > 0$, $\mu_j' \geq 0, \forall j \in J$, and $b_j \geq 0, \forall j \in J$. Therefore, the solution $\left(\lambda_j', \forall j \in J, \mu_j', \forall j \in J, \Delta b_d'\right)$ is feasible to Model (6) when $c = c''$ is set. Therefore, $\Delta b_d^{TRD}(c'') \geq \Delta b_d^{TRD}(c') = \Delta b_d'$. Q.E.D.

**Theorem 4.** Regarding the optimal objective function value $\Delta b_d^{TRD}(c)$ of Model (6) as a function of the trading price $c$, a price $c^{thres} > 0$ of carbon emission permit exists. If $c \geq c^{thres}$ in Model (6), then the optimal objective function value of model (6), that is, $\Delta b_d^{TRD}(c)$, is constant as $c$ increases.

**Proof.** Consider the following Model (7).

$$\Delta b_d^{TRD*} = \max \Delta b_d, \quad (7)$$

$$\text{Subject to} \quad \sum_{j=1}^{n}(\lambda_j + \mu_j)X_j \leq X_d, \quad (7a)$$

$$\sum_{j=1}^{n} \lambda_j Y_j \geq Y_d, \quad (7b)$$

$$\sum_{j=1}^{n} \lambda_j b_j = b_d - \Delta b_d, \quad (7c)$$

$$\sum_{j=1}^{n}(\lambda_j + \mu_j) = 1, \quad (7d)$$

$$\lambda_j \geq 0 \quad \forall j \in J, \quad (7e)$$

$$\mu_j \geq 0 \quad \forall j \in J, \quad (7f)$$

$$\Delta b_d \geq 0. \quad (7g)$$

The optimal solution of Model (6) is a feasible solution of Model (7) due to its transformation from Model (6) by eliminating the constraint (6c). Therefore, $\Delta b_d^{TRD} \leq \Delta b_d^{TRD*}, \forall d \in J$. Assume the optimal solution of Model (7) is $(\lambda'_j, \forall j \in J, \mu'_j, \forall j \in J, \Delta b'_d)$. Let $c^{thres} = \min\{c | \sum_{j=1}^{n}(\lambda'_j g_j + c\mu'_j b_j) \geq g_d\}$. Thus, if $c \geq c^{thres}$, then $\sum_{j=1}^{n}(\lambda'_j g_j + c\mu'_j b_j) \geq g_d$. Hence, if $c \geq c^{thres}$, then $(\lambda'_j, \forall j \in J, \mu'_j, \forall j \in J, \Delta b'_d)$ is also a feasible solution of Model (6). Therefore, $\Delta b_d^{TRD} \geq \Delta b_d^{TRD*}$. $\Delta b_d^{TRD} = \Delta b_d^{TRD*}$ is obtained because $\Delta b_d^{TRD} \leq \Delta b_d^{TRD*}$ is already available. Therefore, if Model (6) shows that $c \geq c^{thres}$, then the optimal objective function value of Model (6), that is, $\Delta b_d^{TRD}(c)$, is constant and equal to $\Delta b_d^{TRD*}$. Q.E.D.

**Remark 4.** Proposition 1 indicates that the DMU has the potential to reduce its carbon dioxide emission after adopting the carbon emission permit trading mechanism. This finding is consistent with and supports the practice of the government (e.g., the European Union and China) of adopting emission trading systems to stimulate the organizations to reduce carbon dioxide emissions.

**Remark 5.** Theorem 3 states that the DMU has more potential to reduce carbon dioxide if the carbon emission permit trading price is increased. This condition indicates that the government could stimulate the DMUs to reduce carbon dioxide emissions by appropriately increasing the trading price of carbon emission permits.

**Remark 6.** Theorem 4 indicates that the carbon dioxide emission abatement potential of the DMU becomes constant when the carbon emission price increases above a threshold value. That is, the carbon dioxide emission abatement potential of the DMU does not rise despite the increase in carbon emission permit price. This condition is consistent with the managerial practice, in which the decisionmakers cannot always stimulate the DMUs to reduce carbon dioxide emissions by increasing the carbon emission permit trading price. This property is called "***limited enhancement property.***"

In summary, organizations show greater potential to reduce carbon dioxide emission when carbon emission permit trading is considered (Proposition 1). Increasing the price of carbon emission permits would, up to a threshold, increase the DMU's carbon emission reduction potential (Theorem 3). However, a limited enhancement property exists, i.e., the carbon dioxide emission abatement potential of the DMU becomes constant when the carbon emission price increases above a threshold value (Theorem 4).

*3.2 Performance evaluation models based on range-adjusted measure*

The models for the efficiency evaluation of the DMUs using the range-adjusted measure (RAM) are introduced in this section. RAM was first proposed by Aida et al. (1998) and Cooper et al. (1999). Moreover, RAM has the advantages of finding inefficiencies of all the inputs and outputs of the DMUs and ensuring an efficient projection target for the DMU. This measure has been extensively adopted for applications in a wide array of areas, including regional energy and environmental efficiency analysis (Wang et al., 2013), eco-efficiency analysis of manufacturing industries (Ramli and Munisamy, 2015), and logistics performance analysis (Rashidi and Cullinane, 2019).

$T^{NTRD}$ is adopted when the carbon emission permit trading is disregarded, and the following Model (8) is proposed for the performance measurement of a DMU $d$.

$$\Theta_d^{NTRD} = \min 1 - \frac{1}{m+s+2}\left(R_X \cdot \Delta X_d + R_Y \cdot \Delta Y_d + R_g \cdot \Delta g_d + R_b \cdot \Delta b_d\right), \quad (8)$$

Subject to $\sum_{j=1}^{n}(\lambda_j + \mu_j)X_j \leq X_d - \Delta X_d,$ (8a)

$\sum_{j=1}^{n}\lambda_j Y_j \geq Y_d + \Delta Y_d,$ (8b)

$\sum_{j=1}^{n}\lambda_j g_j \geq g_d + \Delta g_d,$ (8c)

$\sum_{j=1}^{n}\lambda_j b_j = b_d - \Delta b_d,$ (8d)

$\sum_{j=1}^{n}(\lambda_j + \mu_j) = 1,$ (8e)

$\lambda_j \geq 0 \quad \forall j \in J,$ (8f)

$\mu_j \geq 0 \quad \forall j \in J,$ (8g)

$\Delta X_d \geq \mathbf{0} \in \mathbb{R}_+^{\boldsymbol{m}},\ \Delta Y_d \geq \mathbf{0} \in \mathbb{R}_+^{\boldsymbol{s}}, \Delta g_d \geq 0, \Delta b_d \geq 0$ (8h)

In Model (8), $R_X = \left(\frac{1}{\max_{j\in J}\{x_{1j}\}-\min_{j\in J}\{x_{1j}\}}, \dots, \frac{1}{\max_{j\in J}\{x_{mj}\}-\min_{j\in J}\{x_{mj}\}}\right)$, $R_Y = \left(\frac{1}{\max_{j\in J}\{y_{1j}\}-\min_{j\in J}\{y_{1j}\}}, \dots, \frac{1}{\max_{j\in J}\{y_{sj}\}-\min_{j\in J}\{y_{sj}\}}\right)$, $R_g = \frac{1}{\max_{j\in J}\{g_j\}-\min_{j\in J}\{g_j\}}$, and $R_b = \frac{1}{\max_{j\in J}\{b_j\}-\min_{j\in J}\{b_j\}}$. $\Theta_d^{NTRD} \in [0,1]$ denotes the efficiency of DMU $d$ when carbon emission permit trading is not considered.

$T^{TRD}$ is adopted when carbon emission permit trading is considered, and the following model is established for the performance evaluation of DMU $d$ ($\forall d \in J$).

$$\Theta_d^{TRD} = \min 1 - \frac{1}{m+s+2}\left(R_X \cdot \Delta X_d + R_Y \cdot \Delta Y_d + R_g \cdot \Delta g_d + R_b \cdot \Delta b_d\right), \quad (9)$$

Subject to $\sum_{j=1}^{n}(\lambda_j + \mu_j)X_j \leq X_d - \Delta X_d,$ (9a)

$\sum_{j=1}^{n}\lambda_j Y_j \geq Y_d + \Delta Y_d,$ (9b)

$\sum_{j=1}^{n}(\lambda_j g_j + c\mu_j b_j) \geq g_d + \Delta g_d,$ (9c)

$\sum_{j=1}^{n}\lambda_j b_j = b_d - \Delta b_d,$ (9d)

$\sum_{j=1}^{n}(\lambda_j + \mu_j) = 1,$ (9e)

$\lambda_j \geq 0 \quad \forall j \in J,$ (9f)

$\mu_j \geq 0 \quad \forall j \in J,$ (9g)

$\Delta X_d \geq \mathbf{0} \in \mathbb{R}_+^{\boldsymbol{m}},\ \Delta Y_d \geq \mathbf{0} \in \mathbb{R}_+^{\boldsymbol{s}}, \Delta g_d \geq 0, \Delta b_d \geq 0.$ (9h)

In Model (9), $R_X$, $R_Y$, $R_g$, and $R_b$ are defined as in Model (8). $\Theta_d^{TRD} \in [0,1]$ denotes the efficiency of DMU $d$ when carbon emission permit trading is considered. Assume the optimal solution of Model (9) is $(\lambda_j^*, \forall j \in J, \mu_j^*, \forall j \in J, \Delta X_d^*, \Delta Y_d^*, \Delta g_d^*, \Delta b_d^*)$. On the right-hand side of Model (9), carbon emission permit trading is disregarded when setting the target for the focal DMU. That is to say, when the carbon dioxide emission of the focal DMU must be reduced for performance improvement, the additional monetary output of the DMU is ignored. This finding is due to the intention of Model (9) to compare the focal DMU production with that of DMUs in the PPS to determine the input and output improvements of the focal DMU. More importantly, the production target setting for a DMU is an ex-post estimation procedure, which indicates that the focal DMU has already used up its carbon emission permit in the previous production period. Therefore, the reduction in carbon dioxide emission does not mean that the DMU has excess carbon emission permit to sell. The explanation for Model (6) is similar.

**Proposition 2.** $\Theta_d^{TRD} \leq \Theta_d^{NTRD}, \forall d \in J$

**Proof.** This proof of this proposition resembles the proof of Proposition 1 and is omitted.

The following Corollary 1 is presented in accordance with Theorem 3.

**Corollary 1.** $\Theta_d^{TRD}(c)$ is monotonic non-increasing with the increasing of $c$.

**Proposition 3.** $\Delta b_d^{TRD} \geq \Delta b_d^*,\ \forall d \in J$.

**Proof.** The proof is similar to the proof of Proposition 1 and is omitted.

**Remark 7.** Proposition 2 states that the efficiency of DMU $d$ after adopting the carbon emission permit trading is smaller than without carbon emission permit trading. A small efficiency score of a DMU means that this DMU has additional room for improvements in its inputs and outputs. This finding indicates that the use of the emission trading system has introduced increased potentials for the DMUs to improve their productions. Corollary 1 also indicates that the centralized decisionmaker may increase the potential of DMUs in the production improvement via stimulation by properly increasing the carbon emission permit trading price.

**Remark 8.** Proposition 3 indicates that the reduction target of carbon dioxide of DMU $d$, that is, $\Delta b_d^*$, is generally not larger than its carbon dioxide abatement potential ($\Delta b_d^{TRD}$). $\Delta b_d^{TRD} > \Delta b_d^*$ will generally be obtained because Model (9) considers the improvements of all the inputs and outputs of the DMUs.

## 4. An Illustrative Example

This section uses a numerical example to compare the alternative models and perform a sensitivity analysis of the relationship of carbon emission permit trading price to two values for the DMUs: the carbon dioxide emission abatement potential and the efficiency.

### *4.1 Comparison of different models*

Data of 10 DMUs were randomly generated. Each DMU has one input, one desirable output, one monetary output, and carbon dioxide emission. The raw data of the DMUs are listed in columns 2–5 in Table 1. In this example, the carbon emission permit trading price is set as 30. The calculation results of Models (5) – (9) are listed in columns 6–10 of Table 1.

**Table 1.** Raw data and results of Models (5) – (9).

| DMUs | Inputs | Desirable outputs | Monetary outputs | Undesirable outputs | $\Theta_d^{NTRD}$ | $\Theta_d^{TRD}$ | $\Delta b_d^{NTRD}$ | $\Delta b_d^{TRD}$ | $\Delta b_d^*$ |
|---|---|---|---|---|---|---|---|---|---|
| **A** | 71 | 247 | 993 | 70 | 0.6578 | 0.6523 | 54.59 | 60.30 | 60.30 |
| **B** | 36 | 407 | 1338 | 89 | 1.0000 | 1.0000 | 0.00 | 0.00 | 0.00 |
| **C** | 54 | 262 | 1292 | 53 | 0.8470 | 0.8395 | 17.04 | 28.42 | 26.39 |
| **D** | 22 | 428 | 557 | 70 | 1.0000 | 1.0000 | 0.00 | 0.00 | 0.00 |
| **E** | 27 | 280 | 919 | 11 | 1.0000 | 1.0000 | 0.00 | 0.00 | 0.00 |
| **F** | 57 | 277 | 983 | 43 | 0.8157 | 0.8144 | 27.71 | 29.63 | 29.28 |
| **G** | 28 | 199 | 688 | 75 | 0.6722 | 0.6692 | 66.77 | 67.18 | 65.57 |
| **H** | 56 | 225 | 1002 | 94 | 0.6128 | 0.6050 | 78.05 | 85.16 | 85.16 |
| **J** | 98 | 206 | 1640 | 54 | 1.0000 | 0.6905 | 0.00 | 33.45 | 29.73 |
| **K** | 34 | 315 | 1891 | 87 | 1.0000 | 1.0000 | 0.00 | 0.00 | 0.00 |

Comparing the results generated by Models (8) and (9), the following observations are presented. First, the efficiencies of DMUs B, D, E, and K are maintained after considering carbon emission permit trading, with an efficiency score of 1 before and after considering carbon emission permit trading. Additionally, the potentials of reducing carbon dioxide emission for these efficient DMUs remains at zero. However, DMU J is found to be efficient with consideration of carbon emission permit trading but inefficient without (with an efficiency score of 0.6905). The carbon dioxide emission abatement potential of DMU J also increased from 0 to 33.45 after considering carbon emission permit trading. Second, the efficiencies and carbon dioxide emission abatement potentials of all the other DMUs respectively decreased and increased after considering carbon emission permit trading. For instance, the efficiency of DMU C without (generated from Model (8)) and with (generated from Model (9)) consideration for carbon emission permit trading is 0.8470 and 0.8295, respectively. The carbon dioxide emission abatement potential of DMU C increases from 17.04 to 28.42.

The above observations are consistent with the conclusions in Propositions 1 and 2, that is, $\Delta b_d^{NTRD} \leq \Delta b_d^{TRD}, (\forall d \in J)$ and $\Theta_d^{TRD} \leq \Theta_d^{NTRD}, (\forall d \in J)$. These conclusions indicate that adopting carbon emission permit trading can extend the production technology of the DMUs, thus resulting in additional improvement potential (i.e., lower efficiencies) for the inputs and outputs of DMUs and increased carbon dioxide emission abatement potentials.

The results in Table 1 also indicate that $\Delta b_d^{TRD} \geq \Delta b_d^{*}, (\forall d \in J)$. These results are consistent with the discussion for Proposition 3, which indicates that the focal DMU cannot reduce the amount of carbon dioxide emission by the amount of its total potential if it also improves all of its inputs and outputs when setting production targets.

*4.2 Sensitivity analysis*

The relationship between carbon emission permit trading price and (1) the carbon emission abatement potential and (2) the efficiency of the DMUs, is explored in this section. These relationships have been theoretically discussed in Theorem 3 and Corollary 1, which indicates that the increase of carbon emission permit price would raise the carbon emission abatement and improvement potentials in the inputs and outputs of DMUs (i.e., generally generating lower efficiencies).

*4.2.1 Sensitivity analysis of carbon emission permit trading prices to carbon emission abatement potential*

The scenarios where the carbon emission permit price (in units of yuan/ton) is 10, 15, 20, 25, 30, 35, 40, 45, and 50 are considered, and the carbon emission abatement potential of each DMU is calculated based on Model (7). The calculation results are listed in Table 2. Figure 2 shows the trend of the carbon dioxide emission abatement potentials of the DMUs with the increase of carbon emission permit price.

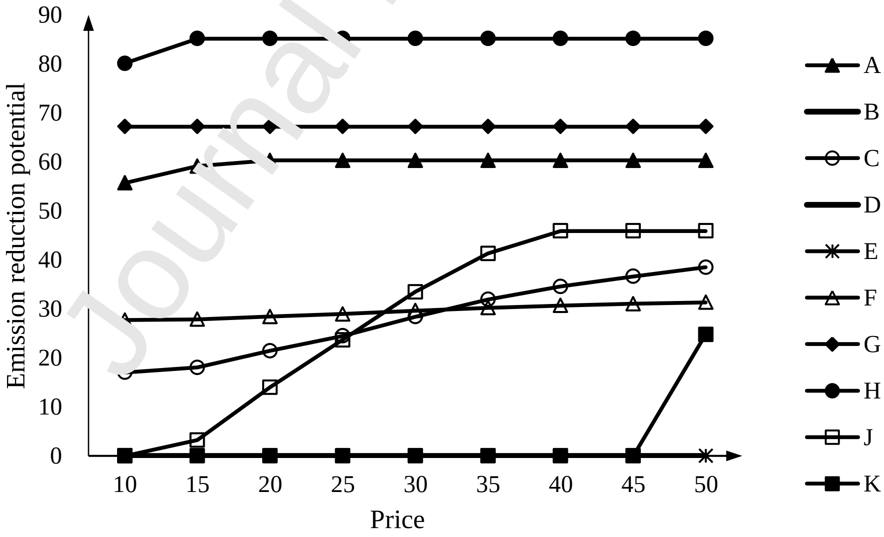


**Figure 2.** Relation between carbon emission permit price and abatement potential

Several observations can be obtained from the calculation results. First, the carbon dioxide emission abatement potentials for DMUs A, C, F, H, J, and K increase with rising carbon emission permit trading price. For instance, the carbon dioxide emission abatement potential of DMU C increases from 17.04 to

38.48 when the carbon emission permit trading price increases from 10 to 50. The limited enhancement property is observed in DMU A. Specifically, when the carbon emission permit trading price increases above 16.48, the carbon dioxide emission abatement potential of DMU A remains at 60.30. Moreover, some DMUs (i.e., DMUs J and K) do not have any potential for reducing their carbon dioxide emission when the carbon emission price is substantially low, but their potentials become positive when the carbon emission trading price increases. Second, the carbon dioxide emission abatement potentials for DMUs B, D, G, and E are maintained with an increasing carbon emission permit trading price. This finding indicates that the increase of carbon emission permit trading price does not affect the benchmark targets for these DMUs.

**Table 2.** Carbon emission abatement potential with alternative carbon prices

| DMUs | 10 | 15 | 20 | 25 | 30 | 35 | 40 | 45 | 50 |
|---|---|---|---|---|---|---|---|---|---|
| A | 55.71 | 59.13 | 60.30 | 60.30 | 60.30 | 60.30 | 60.30 | 60.30 | 60.30 |
| B | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| C | 17.04 | 18.05 | 21.44 | 24.49 | 28.42 | 31.93 | 34.57 | 36.62 | 38.48 |
| D | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| E | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| F | 27.71 | 27.88 | 28.45 | 28.96 | 29.63 | 30.23 | 30.68 | 31.03 | 31.35 |
| G | 67.18 | 67.13 | 67.18 | 67.18 | 67.18 | 67.18 | 67.18 | 67.18 | 67.18 |
| H | 80.10 | 85.16 | 85.16 | 85.16 | 85.16 | 85.16 | 85.16 | 85.16 | 85.16 |
| J | 0.00 | 3.21 | 14.00 | 23.68 | 33.45 | 41.30 | 45.91 | 45.91 | 45.91 |
| K | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 24.76 |

Overall, the increase of carbon emission permit trading price has extended the production technology of the DMUs and thus increased some of their carbon dioxide emission abatement potentials. However, this increment capability is limited because of the limited enhancement property.

*4.2.2 Sensitivity analysis of carbon emission permit trading prices to efficiency*

Table 3 shows the efficiencies of the DMUs calculated by Model (9) when the carbon emission permit trading price ranges from 10 to 50. A clear expression of the relationship is displayed in Figure 3.

**Table 3.** Efficiency evaluation result with alternative carbon emission permit trading prices

| DMUs | 10 | 15 | 20 | 25 | 30 | 35 | 40 | 45 | 50 |
|---|---|---|---|---|---|---|---|---|---|
| A | 0.6578 | 0.6578 | 0.6578 | 0.6578 | 0.6523 | 0.6411 | 0.6084 | 0.5756 | 0.5423 |
| B | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 |
| C | 0.8470 | 0.8470 | 0.8470 | 0.8470 | 0.8395 | 0.8266 | 0.7982 | 0.7677 | 0.7368 |
| D | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 |
| E | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 |
| F | 0.8157 | 0.8157 | 0.8157 | 0.8157 | 0.8144 | 0.8115 | 0.7908 | 0.7633 | 0.7358 |
| G | 0.6722 | 0.6722 | 0.6722 | 0.6722 | 0.6692 | 0.6486 | 0.6081 | 0.5650 | 0.5219 |
| H | 0.6128 | 0.6128 | 0.6128 | 0.6128 | 0.6050 | 0.5874 | 0.5501 | 0.5128 | 0.4751 |
| J | 1.0000 | 0.7794 | 0.7339 | 0.7165 | 0.6905 | 0.6612 | 0.6200 | 0.5788 | 0.5373 |
| K | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 0.9236 |
| Average | 0.8606 | 0.8385 | 0.8340 | 0.8322 | 0.8271 | 0.8176 | 0.7976 | 0.7763 | 0.7473 |

The following observations can be obtained from the results in Table 3. First, DMUs B, D, and E maintain maximum efficiency (i.e., 1) even when the carbon emission permit trading price increases from 10 to 50. The efficiencies of the other DMUs (i.e., seven of the ten DMUs) decrease as the carbon emission permit trading price gradually increases from 10 to 50. For instance, the efficiency of DMU J decreases from 1 to 0.5373 when the carbon emission permit trading price increases from 10 to 50. Additionally, Figure 3 shows that the average efficiency of the DMUs decreases with increasing carbon emission permit trading price. These observations are consistent with the conclusion in Corollary 1, which states that the decisionmaker can stimulate the DMUs to conduct additional improvements on their productions (because decreased efficiencies are obtained with the increasing of the carbon emission permit trading price) through properly increasing the carbon emission permit trading price. Therefore, a new production technology where the DMUs have the potential to conduct additional improvements on their inputs and outputs is introduced.

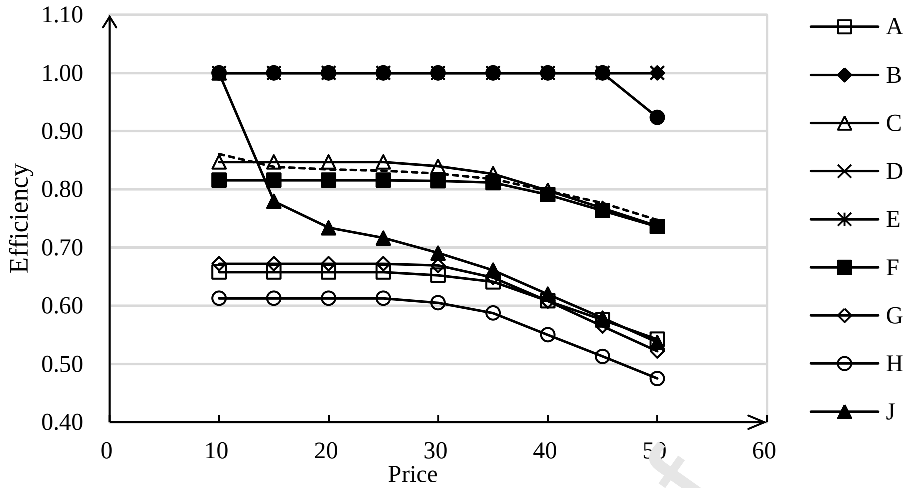


**Figure 3.** Efficiency change with alternative carbon emission permit trading prices

In summary, this section first uses a numerical example to compare our approach with the existing approach that does not consider carbon emission permit trading. The comparison results show that when carbon emission permit trading is adopted, DMUs usually have greater potential for reducing carbon emission, and they get lower efficiencies, which is consistent with our findings in Propositions 1 and 2. The sensitivity analysis shows that increasing the emission permit price typically results in an increase in the DMU's emission abatement potential and a decrease in the DMU's efficiency. Additionally, the limited enhancement property can be clearly seen in the calculation results. These results are consistent with our findings in Theorems 3 and 4.

## 5. An Application to the Thermal Power Industry of China

The proposed approach is applied to a case study of the Chinese thermal power industry in this section to demonstrate its usefulness. The thermal power industry includes all facilities that burn combustible material (e.g., coal) to produce electricity.

### *5.1 Data and Variables*

Carbon dioxide emission is one of the main by-products of the Chinese thermal power industry.

According to Global Energy & $CO_2$ Status Report 2019, the thermal power industry emitted 13GT $CO_2$, which accounts for 38% of total energy-related $CO_2$ emissions in 2018. Investigating the thermal power industry is essential to achieve the goal of China in carbon dioxide emission abatement. Such an investigation also aims to estimate the carbon dioxide emission abatement potential and set the production target for each region in China to guide its future production. The presented analysis uses data from 2011 to 2016, collected from 29 mainland China regions. Some data for 2017–2019 is unavailable; thus, only the data from 2011 to 2016 are considered. Each region is regarded as a DMU, and the production data of its thermal power industry are analyzed.

Following studies (e.g., Yang et al. 2010; Liu et al. 2017; Wang et al. 2019) focusing on the analysis of the thermal power industry, we select energy consumption, installed capacity, and labor force as the inputs for each region. Data on installed capacity and labor force are collected from the Chinese Electricity Power Yearbook (2012–2017) and the National Bureau of Statistics, respectively. A detailed discussion of how the energy consumption data are obtained is provided in Appendix B. The outputs comprise electricity generation, carbon dioxide emission, and the funding pool of environmental protection in each region. The data on electricity generation are collected from the National Bureau of Statistics. Carbon dioxide emission in each region is computed by the Intergovernmental Panel on Climate Change (IPCC) Sectoral Approach, which has been widely adopted in the previous studies (e.g., Fujii et al. 2015, Wu et al. 2016, An et al. 2017, Zhang et al. 2018, and Zhang et al. 2020). The funding pool of environmental protection is selected as another output, which is also the monetary output that is affected by the carbon emission permit trading of DMUs. According to the China Statistic Year Book 2019, the average investment of China on environment treatment during 2011–2016 was approximately 0.8 trillion RMB, which accounts for approximately 1% of the average GDP of China during those years.

Moreover, the Chinese government introduced the policy of "those who pollute must treat". Therefore, the thermal power industry in each region must invest in environmental treatment to meet the environmental standards required by the government. Therefore, 1% of the revenue generated by the thermal power industry is assumed to be the funding pool for environmental protection. The inputs and outputs of the regions are described as follows: $x_1$: Energy consumption ($10^4$ tons/tce); $x_2$: Installed capacity ($10^4$ kWh); $x_3$: Labor force ($10^4$ person); $y$: Electricity generation ($10^8$ kWh); $m$: Funding pool ($10^6$ RMB); $p$: Carbon dioxide emission ($10^4$ tons).

Table 4 provides a descriptive statistical analysis of the production data of the 29 regions. A decreasing trend of energy consumption and carbon dioxide emission from 2011 to 2016 is observed. China had not yet adopted the emission trading system in 2011 and 2012; thus, the trading price for carbon emission permits is unavailable in those years. The average carbon emission permit trading price from 2013 to 2016 is listed in Table 5 (data collected from the CSMAR database).

**Table 4.** Descriptive statistics analysis of the raw data

| Year | | $x_1$ | $x_2$ | $x_3$ | $y$ | $m$ | $p$ |
|---|---|---|---|---|---|---|---|
| 2011 | Mean | 4311.64 | 2592.38 | 11.25 | 1296.60 | 505.71 | 7524.69 |
| | Median | 3619.47 | 1918.00 | 9.75 | 913.63 | 392.86 | 6289.74 |
| | S.D. | 3066.93 | 1887.07 | 5.59 | 972.43 | 412.61 | 5423.89 |
| | Min. | 320.13 | 230.00 | 1.45 | 91.78 | 28.36 | 424.50 |
| | Max. | 11507.06 | 6480.00 | 21.46 | 3562.63 | 1505.97 | 20257.88 |
| 2012 | Mean | 4131.63 | 2747.41 | 11.59 | 1274.45 | 528.15 | 7203.76 |
| | Median | 3518.58 | 2118.00 | 9.88 | 882.45 | 360.99 | 5947.80 |
| | S.D. | 2963.20 | 1969.37 | 5.73 | 981.18 | 431.81 | 5238.08 |
| | Min. | 328.08 | 230.00 | 1.98 | 114.70 | 38.88 | 458.54 |
| | Max. | 11261.95 | 6982.00 | 22.50 | 3669.74 | 1614.69 | 19803.46 |
| 2013 | Mean | 3672.93 | 2898.03 | 13.63 | 1417.45 | 566.72 | 6389.13 |
| | Median | 3083.53 | 2127.00 | 13.36 | 1011.60 | 409.57 | 5176.75 |
| | S.D. | 2640.27 | 2115.73 | 7.37 | 1082.30 | 452.62 | 4663.78 |
| | Min. | 314.73 | 235.00 | 1.85 | 134.43 | 44.36 | 447.37 |
| | Max. | 9509.50 | 7555.00 | 32.18 | 4099.24 | 1701.18 | 16703.65 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 2014 | Mean | 3398.37 | 3082.86 | 13.56 | 1399.11 | 544.42 | 5897.48 |
| | Median | 2775.83 | 2138.00 | 13.42 | 933.34 | 350.27 | 4545.15 |
| | S.D. | 2505.75 | 2256.30 | 7.20 | 1099.99 | 440.20 | 4426.80 |
| | Min. | 295.77 | 242.00 | 1.89 | 129.86 | 42.46 | 419.13 |
| | Max. | 9273.31 | 8073.00 | 30.80 | 4049.84 | 1636.14 | 16278.23 |
| 2015 | Mean | 3183.22 | 3321.24 | 13.31 | 1391.70 | 564.34 | 5471.57 |
| | Median | 2484.19 | 2261.00 | 13.00 | 962.35 | 344.30 | 4332.00 |
| | S.D. | 2408.77 | 2440.94 | 7.14 | 1175.34 | 497.20 | 4247.99 |
| | Min. | 308.17 | 318.00 | 1.96 | 122.00 | 38.21 | 416.92 |
| | Max. | 9100.82 | 8754.00 | 30.71 | 4502.09 | 2009.55 | 15912.01 |
| 2016 | Mean | 3301.28 | 3492.38 | 13.01 | 1453.43 | 531.41 | 5650.83 |
| | Median | 2652.76 | 2322.00 | 12.35 | 900.20 | 324.42 | 4619.34 |
| | S.D. | 2493.62 | 2558.31 | 7.01 | 1278.72 | 486.18 | 4390.93 |
| | Min. | 302.18 | 402.00 | 2.16 | 152.19 | 39.30 | 342.75 |
| | Max. | 9485.61 | 9540.00 | 31.27 | 5142.88 | 1987.83 | 16525.78 |

**Table 5.** Average carbon emission permit trading price (unit: yuan/ton)

| Year | 2013 | 2014 | 2015 | 2016 |
|---|---|---|---|---|
| Average Price | 66.854 | 43.691 | 31.329 | 27.097 |

*5.2 Result and Analysis*

Models (5) and (6) are used to calculate the carbon dioxide emission abatement potentials of the regions; the results are listed in Table 6. The average potentials of the DMUs are also computed, listed in the last column of Table 7, and visually displayed in Figure 4.

**Table 6.** Carbon dioxide emission abatement potentials of the regions (unit: $10^4$ tons)

| Regions | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | Average |
|---|---|---|---|---|---|---|---|
| Anhui | 1823.88 | 1753.88 | 1274.01 | 1355.72 | 1275.37 | 1220.12 | 1450.5 |
| Beijing | 492.17 | 340.5 | 120.52 | 0 | 0 | 0 | 158.87 |
| Chongqing | 0 | 2374.81 | 1392.68 | 1592.19 | 1690.2 | 1596.98 | 1441.14 |
| Fujian | 534.55 | 838.67 | 347.02 | 288.55 | 682.28 | 1040.3 | 621.9 |
| Gansu | 1084.05 | 1119.13 | 1077.8 | 1139.86 | 1356.07 | 1539.61 | 1219.42 |
| Guangdong | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Guangxi | 1704.39 | 1733.71 | 1242.83 | 1365.12 | 1644.5 | 1909.53 | 1600.01 |
| Guizhou | 3085.87 | 3506.79 | 3008.36 | 2999.84 | 3133.56 | 3365.06 | 3183.25 |
| Hainan | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Hebei | 0 | 0 | 5708.48 | 4833.85 | 0 | 4265.24 | 2467.93 |
| Heilongjiang | 4476.07 | 4623.89 | 4064.06 | 3846.68 | 3903.13 | 4390.45 | 4217.38 |
| Henan | 6935.92 | 5086.63 | 3790.92 | 3548.51 | 3709.08 | 3882.74 | 4492.3 |
| Hubei | 5376.1 | 5584.62 | 2832.73 | 2780.02 | 2794.95 | 2927.75 | 3716.03 |
| Hunan | 4024.6 | 3763.26 | 2877.22 | 2814.68 | 3187.14 | 3538.27 | 3367.53 |
| Inner Mongolia | 7849.89 | 8072.48 | 0 | 0 | 0 | 6422.94 | 3724.22 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Jiangsu | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Jiangxi | 1636.64 | 1570.9 | 1306.36 | 1373.76 | 1564.35 | 1491.67 | 1490.61 |
| Jilin | 3924.96 | 3797.38 | 3124.92 | 2898.62 | 2968.32 | 3036.8 | 3291.83 |
| Liaoning | 5435.67 | 5127.96 | 4674.92 | 4225.32 | 3803.32 | 3904.92 | 4528.68 |
| Ningxia | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Qinghai | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Shaanxi | 3413.75 | 4188.4 | 0 | 0 | 3109.34 | 3333.34 | 2340.8 |
| Shandong | 9720.17 | 10051.56 | 6932.54 | 7115.17 | 0 | 0 | 5636.57 |
| Shanghai | 57.57 | 29.49 | 0 | 0 | 0 | 0 | 14.51 |
| Shanxi | 8710.32 | 8640.18 | 8537.86 | 8551.32 | 8739.71 | 8801.97 | 8663.56 |
| Sichuan | 4087.44 | 4133.97 | 3629.23 | 3281.46 | 3083.85 | 3254.48 | 3578.4 |
| Tianjin | 0 | 371.34 | 310.84 | 604.18 | 394.12 | 324.7 | 334.2 |
| Yunnan | 3390.56 | 3502.6 | 3171.59 | 2764.33 | 2704.69 | 2816.46 | 3058.37 |
| Zhejiang | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Average | 2681.54 | 2765.94 | 2049.13 | 1978.59 | 1713.31 | 2174.60 | 2227.52 |

Several conclusions can be drawn from the calculation results. First, Jiangsu, Zhejiang, Hainan, Qinghai, Ningxia, and Guangdong do not have any potential for reducing carbon dioxide emissions during the study period. This finding indicates that all these regions consistently use frontier technology in the thermal power industry. Moreover, most of these regions (except Ningxia and Qinghai) are southeastern coastal regions, which benefit from the developed economy of the southeastern coastal regions. Thus, these regions have additional resources that support them to adopt advanced technology (especially pollution treatment technologies) in the thermal power industry. Second, Figure 4 indicates that Shanxi has the largest carbon dioxide emission abatement potential, followed by Shandong. Moreover, the northeast regions (such as Heilongjiang, Jilin, and Liaoning), the southwest regions (such as Sichuan, Guizhou, and Yunnan), and the central regions (such as Henan, Hubei, and Hunan) have considerably large potentials for reducing carbon dioxide emission, ranging from 30 million to 50 million tons. On average, each region has the potential to reduce more than 20 million tons of carbon dioxide emissions. This finding indicates that achieving low carbon dioxide emission in the thermal power industry of China still has a long way to go.

Models (8) and (9) are then used to calculate efficiencies for the regions. Table 7 lists the efficiency evaluation results. Moreover, the carbon dioxide emission reduction targets of the DMUs obtained by Models (8) and (9) are listed in Table 8. Consider the following observations based on the efficiency evaluation and the target setting results of carbon dioxide emission reduction. First, six of the DMUs (Jiangsu, Zhejiang, Hainan, Qinghai, Ningxia, and Guangdong) have efficiencies of 1 from 2011 to 2016. This finding indicates that all these regions consistently perform on the efficient frontier. Thus, reducing carbon dioxide emissions in the target setting results is unnecessary in these regions. Moreover, the southeast regions generally have better performance than other regions in the areas in China. Second, the efficiencies of the thermal power industries in the regions are usually high, and the average efficiencies of the DMUs from 2011 to 2016 are almost all close to 0.9. Moreover, after adopting the emission trading system in 2013, the average efficiency is reduced from 0.9067 in the year 2012 to 0.8940. From 2013 to 2015, the average efficiency gradually increased, which indicates a gradual improvement in the production performance of the thermal power industry in China.

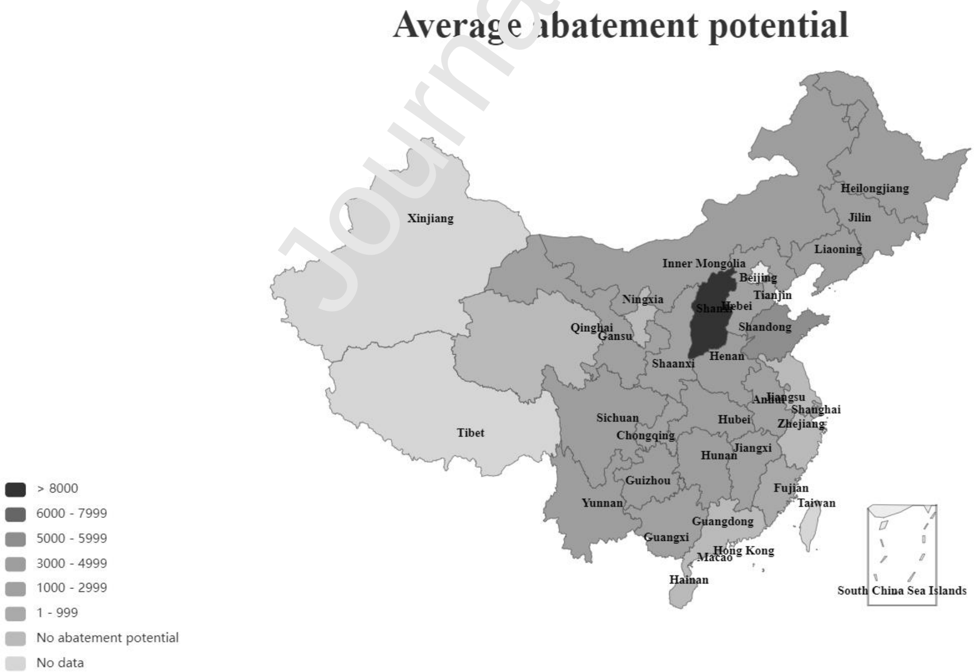


**Figure 4.** Distribution of average abatement potential (unit: $10^4$ tons)

Moreover, a phenomenon is observed that the carbon emission abatement targets of some regions suddenly reduced in the year 2013. For instance, Inner Mongolia's carbon emission abatement target in 2012 is 76.7508 million tons, but it reaches zero in 2013. Similar situations can be seen in Beijing and Shaanxi. China officially launched the emission trading system and used the "cap and trade" principle in the year 2013, which meant that each organization faced the situation of having a limited amount of emission permit and needing to buy additional emission permit from the market if its allowed emission permit could not cover its amount of carbon dioxide emission. Such a situation would bring the organizations uncertain costs if their carbon emission exceeds the allowed emission permits in 2013. Some organizations in certain regions (e.g., Beijing, Inner Mongolia, and Shaanxi) may not wish to take the risk of facing uncertain costs, preferring to adopt advanced technology in advance to reduce their carbon dioxide emissions. This explains why in those regions, carbon emission abatement targets suddenly declined in 2013. However, we also observe that later, in 2015 and 2016, the regions' carbon emission abatement targets rise again. For instance, the carbon emission abatement target of Shaanxi increases from 0 in 2014 to 31.09 million tons in 2015. Observing the original production data of Inner Mongolia, we find that its fundamental inputs (i.e., installed capacity and labor force) increased, i.e., the production scale of thermal power industry in this region reached a high enough level, which helped it to overcome the technical threshold and qualify it to adopt advanced technology like in Zhejiang and Jiangsu to further improve its carbon dioxide emission reduction. A similar situation can be seen for Shaanxi. Also, we need to note that the technological advancement in handling carbon dioxide emission may also cause fluctuations in the carbon emission abatement targets of the DMUs.

**Table 7.** Efficiency evaluation results

| Regions | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 |
|---|---|---|---|---|---|---|
| Anhui | 0.9525 | 0.9488 | 0.9505 | 0.9494 | 0.9522 | 0.9529 |
| Beijing | 0.9340 | 0.9387 | 0.9521 | 1.0000 | 1.0000 | 1.0000 |
| Chongqing | 1.0000 | 0.9189 | 0.9441 | 0.9175 | 0.9349 | 0.9442 |
| Fujian | 0.9696 | 0.9482 | 0.9687 | 0.9764 | 0.9591 | 0.9412 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Gansu | 0.9478 | 0.9469 | 0.9046 | 0.8945 | 0.9190 | 0.9167 |
| Guangdong | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 |
| Guangxi | 0.9306 | 0.9204 | 0.9017 | 0.8882 | 0.9015 | 0.8981 |
| Guizhou | 0.9171 | 0.9067 | 0.8538 | 0.8532 | 0.8804 | 0.8822 |
| Hainan | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 |
| Hebei | 1.0000 | 1.0000 | 0.8429 | 0.8614 | 1.0000 | 0.8654 |
| Heilongjiang | 0.8332 | 0.8214 | 0.7466 | 0.8034 | 0.8343 | 0.8376 |
| Henan | 0.8016 | 0.8088 | 0.7771 | 0.7940 | 0.8262 | 0.8118 |
| Hubei | 0.8052 | 0.7799 | 0.8201 | 0.8211 | 0.8753 | 0.8783 |
| Hunan | 0.8607 | 0.8419 | 0.8201 | 0.8318 | 0.8504 | 0.8575 |
| Inner Mongolia | 0.7956 | 0.7961 | 1.0000 | 1.0000 | 1.0000 | 0.8132 |
| Jiangsu | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 |
| Jiangxi | 0.9215 | 0.9170 | 0.9075 | 0.9044 | 0.9179 | 0.9508 |
| Jilin | 0.8781 | 0.8791 | 0.7813 | 0.8353 | 0.8746 | 0.8894 |
| Liaoning | 0.8092 | 0.8162 | 0.7596 | 0.8215 | 0.8713 | 0.8731 |
| Ningxia | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 |
| Qinghai | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 |
| Shaanxi | 0.9064 | 0.8906 | 1.0000 | 1.0000 | 0.8921 | 0.8902 |
| Shandong | 0.7720 | 0.7432 | 0.7101 | 0.7460 | 1.0000 | 1.0000 |
| Shanghai | 0.9932 | 0.9895 | 1.0000 | 1.0000 | 1.0000 | 1.0000 |
| Shanxi | 0.8195 | 0.8145 | 0.7683 | 0.7742 | 0.7786 | 0.7660 |
| Sichuan | 0.8183 | 0.8067 | 0.7243 | 0.7608 | 0.7883 | 0.8124 |
| Tianjin | 1.0000 | 0.9874 | 0.9865 | 0.9690 | 0.9874 | 0.9881 |
| Yunnan | 0.8869 | 0.8729 | 0.8059 | 0.8411 | 0.8773 | 0.8822 |
| Zhejiang | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 |
| Average | 0.9150 | 0.9067 | 0.8940 | 0.9049 | 0.9283 | 0.9190 |

Finally, let us compare the carbon dioxide emission reduction targets provided in Table 8 and the carbon dioxide emission abatement potentials of the DMUs given in Table 6. This comparison reveals that the regions usually cannot attain their full potential in reducing carbon dioxide emission when making reduction targets if they consider improvements not only of the indicator of carbon dioxide emission but also their other inputs and outputs. This finding is consistent with Proposition 3. Nevertheless, these results typically require the DMUs with large carbon dioxide emission abatement potentials to reduce their carbon dioxide emissions.



**Table 8.** Carbon dioxide emission reduction targets (unit: $10^4$ tons)

| Region | Models (8) and (9) | | | | | |
|---|---|---|---|---|---|---|
| | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 |
| Anhui | 1247.73 | 1216.04 | 1175.44 | 1230.84 | 1074.08 | 910.51 |
| Beijing | 408.52 | 265.94 | 66.96 | 0 | 0 | 0 |
| Chongqing | 0 | 2260.39 | 1338.5 | 1476.38 | 1367.19 | 1224.39 |
| Fujian | 92.35 | 165.08 | 287.31 | 85.8 | 304.6 | 524.08 |
| Gansu | 613.69 | 733.03 | 819.27 | 897.79 | 833.43 | 849.6 |
| Guangdong | 0 | 0 | 0 | 0 | 0 | 0 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Guangxi | 1346.06 | 1364.06 | 970.74 | 1161.14 | 1169.22 | 1240.15 |
| Guizhou | 2348.2 | 2899.81 | 2468.17 | 2646.9 | 2554.86 | 2710.19 |
| Hainan | 0 | 0 | 0 | 0 | 0 | 0 |
| Hebei | 0 | 0 | 5708.48 | 4726.1 | 0 | 4143.21 |
| Heilongjiang | 3953.24 | 4204.8 | 3666.66 | 3580.07 | 3361.38 | 3680.35 |
| Henan | 4969.95 | 3477.56 | 2822.88 | 2870.74 | 2788.34 | 2905.17 |
| Hubei | 4822.83 | 5077.1 | 2305.8 | 2449.9 | 2199.57 | 2176.32 |
| Hunan | 3658.7 | 3107.95 | 2430.85 | 2557.41 | 2653.65 | 2836.06 |
| Inner Mongolia | 7556.9 | 7675.08 | 0 | 0 | 0 | 6135.49 |
| Jiangsu | 0 | 0 | 0 | 0 | 0 | 0 |
| Jiangxi | 1286.39 | 1151.46 | 1009.11 | 1219.84 | 1116.28 | 956.4 |
| Jilin | 3554.98 | 3516.82 | 2784.25 | 2685.38 | 2471.78 | 2363.18 |
| Liaoning | 4496.8 | 4336.73 | 4008.09 | 3777.1 | 3334.12 | 3310.05 |
| Ningxia | 0 | 0 | 0 | 0 | 0 | 0 |
| Qinghai | 0 | 0 | 0 | 0 | 0 | 0 |
| Shaanxi | 2592.63 | 3721.1 | 0 | 0 | 3109.34 | 3242.66 |
| Shandong | 7778.14 | 8541.58 | 6235.35 | 66[illegible]3.77 | 0 | 0 |
| Shanghai | 19.66 | 0 | 0 | 0 | 0 | 0 |
| Shanxi | 8298.24 | 8158.34 | 8218.16 | 8182.41 | 8441.52 | 8325.16 |
| Sichuan | 3702.6 | 3841.25 | 3278.71 | 3089.06 | 2616.91 | 2643.37 |
| Tianjin | 0 | 260.3 | 310.84 | 519.51 | 336.27 | 227.45 |
| Yunnan | 3068.18 | 3295.11 | 2887.77 | 2634.66 | 2466.09 | 2484.94 |
| Zhejiang | 0 | 0 | 0 | 0 | 0 | 0 |

*5.3 Policy and managerial implications*

Some basic policy implications can be concluded based on the above analysis. First, if the Chinese government aims to reduce carbon dioxide emission in the thermal power industry, then additional attention must be provided to restrict the emission of regions in China's northeast, central, and the southwest areas, for instance, Shanxi, Shandong, Heilongjiang, Jilin, Liaoning, Sichuan, Chongqing, Yunnan, and Guizhou, because these regions have considerably large potentials for reducing carbon dioxide emissions. The research results indicate that the government could also properly upregulate the carbon emission trading price to simulate the DMUs to reduce their carbon dioxide emission. Third, the regions that wish to adopt advanced technology in the thermal power industry to reduce carbon dioxide emissions could learn from the benchmarks in the southeast areas, such as Zhejiang, Jiangsu, and Guangdong.

Several managerial implications can also be observed from our analysis results. First, the use of the "cap and trade" policy challenges organizations because the policy is enforced with limited emission permits but simultaneously provides them more opportunities through adopting market incentives. Organizations can determine proper carbon dioxide emission reduction plans according to the emission abatement potentials and the benchmarks obtained by our approach. Additionally, the organizations could also consider grasping this opportunity to adopt more advanced technology to handle carbon dioxide emission, which would not only bring them the reputation of strong social responsibility but also bring profit from selling the excess part of their emission permits, thereby enhancing their financial performance. Moreover, the organizations may also investigate whether they need to appropriately increase their fundamental inputs, for instance, installed capacity and labor force. Doing so might help them reach the technical threshold above which it is optimal to adopt more advanced technology and more greatly reduce their carbon dioxide emission.

## 6. Conclusions and directions for future study

This paper develops a new methodology for the performance evaluation of organizations with carbon emission permit trading. The results indicate that standard productions cannot reflect the practical situation if carbon emission permit trading is adopted. Modified production axioms considering carbon emission permit trading are discussed, and new production technology is established. Models based on the new production technology are built to investigate the carbon dioxide emission reduction and performance evaluation of the DMUs. The adoption of the carbon emission trading opens up more possible productions for the DMUs, which introduce considerable potential for DMUs to reduce their carbon dioxide emission and improve their inputs and outputs in the target setting. The proposed approach is compared with the previous approach with a numerical example and validated to be useful by a case study of China's thermal power industry.

The present study contributes to the literature by filling the research gap due to the lack of published research on how adopting carbon emission permit trading affects the production technology in DEA. Details of contributions are as follows. First, the effects of carbon emission permit trading on the production axioms are discussed, and the new production technology is established. Second, new models are proposed to estimate the carbon dioxide emission reduction potential and evaluate efficiency for the DMUs. Third, the analysis provides explicit illustrations of how adopting carbon emission trading impacts both the carbon dioxide emission reduction potential and the efficiency of DMUs.

The presented methodology suggests several future research directions. First, this study reveals that the carbon emission price affects the DMUs' potential for carbon dioxide emission reduction. Future studies may consider the possibility of pricing carbon dioxide emission permits using a production frontier-based analysis. Second, an empirical analysis direction could use the newly built production technology to estimate the carbon emission potential for other types of DMUs, such as the EU countries. This technology can also be used to determine whether carbon dioxide emission reduction targets are realizable considering the consistent exploitation of the frontier and exploration of production technologies. Third, our analysis results show that a slight increase in the production scale of a region can result in a great increase of its carbon emission reduction potential. Therefore, we suggest that scholars investigate whether the converse is possible, that a DMU's carbon emission reduction potential could be reduced by expanding its production scale. This is, in fact, very practical for industries where there exists a production scale threshold affecting whether it is practical to adopt advanced technology for carbon emission reduction. Furthermore, our methodology was developed considering only the "trade" principle and assumed each DMU possesses the amount of carbon emission permit equal to the amount it produces. Future studies may also explore the necessity of using the "cap" principle, i.e., setting an upper bound on each organization's emission amount of carbon dioxide, and build the corresponding methodology considering the "cap and trade" principle. Finally, future studies may also investigate how to allocate limited emission permits among the DMUs considering incentives from the emission trading market.

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## Appendices

*Appendix A. Production technology under the CRS assumption with carbon emission permit trading*

The traditional cone-convexity axiom without the consideration of carbon emission permit trading can be presented as follows.

**Axiom 5.** *Cone-convexity*: $(X, Y, g, b) \in T$ and $\beta \geq 0$ imply that $(\beta X, \beta Y, \beta g, \beta b) \in T$.

Axiom 5 indicates that proportional expansion or curtailment of an observed DMU also belongs to $T$. However, this axiom fails to reflect the practical situation when carbon emission permit trading is considered. Specifically, the following two cases can be considered.

**Case 2.** In Axiom 5, if $0 \leq \beta < 1$, then the amount of carbon dioxide production of the DMU $(\beta X, \beta Y, \beta g, \beta b)$ is reduced to $\beta b$. According to Assumption 1, the DMU possesses a carbon emission permit of amount $b$, which is larger than the amount of carbon dioxide production. Therefore, the DMU would sell the excess part of its carbon emission permit (i.e., $(1-\beta)b$), thus increasing the monetary output to $\beta g + c(1-\beta)b$.

**Case 3.** In Axiom 5, if $\beta > 1$, then the amount of carbon dioxide production of the DMU increases to $\beta b$. The carbon emission permit of such a DMU cannot cover its actual carbon emission amount. Therefore, the DMU must buy additional carbon emission permit amounts, thus decreasing its monetary output to $\beta g - c(\beta - 1)b$.

In managerial practice, assuming that a DMU can expand its production proportionally without limitation is generally inappropriate. Moreover, no real-world organization would buy an unlimited amount of carbon emission permits. With respect to such consideration, it is appropriate to put an upper bound on $\beta$, that is, $0 \leq \beta \leq \beta^U$, where $\beta^U \geq 1$ is a predetermined upper bound for $\beta$.

Based on the above analysis, a new Axiom A5* is presented as follows.

**Axiom 5*.** *Cone-convexity considering carbon emission permit trading*: $(X, Y, g, b) \in T$ implies that $(\beta X, \beta Y, \beta g + c(1-\beta)b, \beta b) \in T$, where $0 \le \beta \le \beta^U$. $\beta^U \ge 1$ is upper bound for $\beta$.

**Theorem A1.** *Let $T$ satisfy Axioms 5* and 3. Then $T$ satisfies Axiom 4*.*

**Proof.** *If $T$ satisfies Axiom 5* and $(X, Y, g, b) \in T$, then $(\beta X, \beta Y, \beta g + c(1-\beta)b, \beta b) \in T$, where $0 \le \beta \le \beta^U$ and $\beta^U \ge 1$. $T$ also satisfies Axiom 3. Thus, $X' \ge \beta X$, $Y' \le \beta Y$, $g' \le \beta g + c(1-\beta)b$, and $b' = \beta b$ such that $(X', Y', g', b') \in T$. Hence, $\alpha = \beta \in [0,1]$, $X' \ge \alpha X$, $Y' \le \alpha Y$, $g' \le \alpha g + c(1-\alpha)b$, and $b' = \alpha b$ must be provided such that $(X', Y', g', b') \in T$. $X \ge \alpha X$ must hold because $\alpha \in [0,1]$. Then, let $X' = X$, $Y' = \alpha Y$, $g' = \alpha g + c(1-\alpha)b$, and $b' = \alpha b$ such that $(X', Y', g', b') = (X, \alpha Y, \alpha g + c(1-\alpha)b, \alpha b) \in T$. Therefore, $(X, Y, g, b) \in T$ and $0 \le \alpha \le 1$ imply that $(X, \alpha Y, \alpha g + c(1-\alpha)b, \alpha b) \in T$.* Q.E.D.

**Definition A1.** Let $T^{TRD-C}$ denote the CRS technology considering carbon emission permit trading. $T^{TRD-C} = (X, Y, g, b) \in \mathbb{R}_+^{m+s+2}$ is the intersection of all the productions satisfying Axioms 1, 2, 3, and 5*.

**Theorem A2.** *$T^{TRD-C}$ is the set of all DMUs $(X, Y, g, b) \in \mathbb{R}_+^{m+s+2}$, in which $\lambda_j \ge 0, \forall j \in J$ and $u_j \ge 0, \forall j \in J$ such that the following conditions are true:*

$$\sum_{j=1}^{n} \lambda_j X_j \le X \quad \text{(A1a)}$$

$$\sum_{j=1}^{n} \lambda_j Y_j \ge Y \quad \text{(A1b)}$$

$$\sum_{j=1}^{n} \left[\lambda_j g_j + c\left(u_j - \lambda_j\right) b_j\right] \ge g \quad \text{(A1c)}$$

$$\sum_{j=1}^{n} \lambda_j b_j = b \quad \text{(A1d)}$$

$$0 \le \lambda_j \le \beta^U u_j \qquad \forall j \in J \quad \text{(A1g)}$$

$$u_j \geq 0 \qquad \forall j \in J \qquad \text{(A1h)}$$

**Proof.** According to Axioms 1–3 and 5*, if $(X, Y, g, b) \in \mathbb{R}_+^{m+s+2}$ contains all the productions satisfying these axioms, then the following conditions are satisfied.

$$\sum_{j=1}^{n} u_j \beta_j X_j \leq X \qquad \text{(A2a)}$$

$$\sum_{j=1}^{n} u_j \beta_j Y_j \geq Y \qquad \text{(A2b)}$$

$$\sum_{j=1}^{n} u_j \left[\beta_j g_j + c(1-\beta_j) b_j\right] \geq g \qquad \text{(A2c)}$$

$$\sum_{j=1}^{n} u_j \beta_j b_j = b \qquad \text{(A2d)}$$

$$u_j \geq 0 \qquad \forall j \in J \qquad \text{(A2g)}$$

$$0 \leq \beta_j \leq \beta^U \qquad \forall j \in J \qquad \text{(A2h)}$$

Let $\lambda_j = u_j \beta_j, \forall j \in J$. Hence, $\lambda_j \geq 0 \ \forall j \in J$ because $\beta_j \geq 0, \forall j \in J$ and $u_j \geq 0, \forall j \in J$. The above formulations can be transformed into the equations in (A1). Q.E.D.

Similar to the relationship between the conventional CRS and VRS DEA production technologies, the main difference between our new CRS and VRS production technologies is that the CRS production technology adopts the cone-convexity production axiom while the VRS production technology does not include this axiom. The cone-convexity production axiom says that a proportional expansion or curtailment of an observed DMU's production also belongs to T. Therefore, in our new CRS production technology, we can always expect to have a production that is a proportional expansion or curtailment of an observed DMU's production, while this is not true for our VRS production technology. Additionally, compared with the conventional VRS and CRS production technologies, our new production technologies have further considered the emission permit trading assumption, which leads to changes to the conventional cone-convexity and weak disposability axioms (see Axiom 4* and Axiom 5*).

Therefore, adapted production axioms are used, and different mathematical formulations are obtained in our new CRS and VRS production technologies.

*Appendix B. Data processing*

The energy consumption of each region's fire power industry is approximately calculated using the following equation:

$$RC_d = C_d * \frac{TF}{T} * p_d, \tag{10}$$

where $RC_d$ denotes the regional energy consumption of the fire power industry of the $d^{th}$ region. $TF$, $T$, $C_d$, and $p_d$ denote the total energy consumption of China's power industry, total energy consumption, energy consumption of the $d^{th}$ region, and percentage of electricity generated by the fire power industry in the $d^{th}$ region, respectively. $\frac{TF}{T}$ is the percentage of energy consumed by the power industry in China, which is used to represent approximately the percentage of energy consumed by the power industry in each region. Then, $C_d * \frac{TF}{T}$ can be regarded as the energy consumed by the fire power industry in each region. Furthermore, $C_d * \frac{TF}{T} * p_d$ obtains the energy consumption of the fire power industry in the $d^{th}$ region.

# Credit Author Statement

**Junfei Chu:** Conceptualization, Methodology, Software, Writing.

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# Highlights

- Emission trading mechanism is investigated for organization performance evaluation.
- New production technology considering carbon emission trading is built.
- Models are proposed to estimate carbon emission potential and evaluate efficiency.
- Adoption effects of carbon emission permit trading is explicitly explained.
- China’s thermal industry is investigated.