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Would China's power industry benefit from nationwide carbon emission permit trading? An optimization model-based ex post analysis on abatement cost savings

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Abstract: The nationwide carbon emission permit trading scheme has been launched in China's power industry sector by the end of 2017. The estimation of abatement costs savings from carbon emission permit trading can provide valuable guidelines and support to environmental regulatory policies on controlling CO_2 emissions. By applying a parametric and nonparametric integrating approach and conducting an ex post analysis in two scenarios (i.e., with and without carbon emission permit trading simulation), this study provides a simulative calculation of the opportunity abatement cost savings and the marginal abatement cost savings from carbon emission permit trading in China's power industry of 30 provinces. The simulation results show that: i) A 13% annually average potential on the opportunity abatement cost savings (i.e., 1024 billion yuan) would be realized if introducing a nationwide emission permit trading system in China's power industry during 2011-2015. ii) Meanwhile, the marginal abatement cost savings that range from 39 to 47 yuan/ton would be realized through emission permit trading. iii) Provinces of Xinjiang and Henan show the largest absolute opportunity abatement cost savings from trading, while Qinghai province shows the highest percentage increase in opportunity abatement cost savings. iv) Although there is significant difference in the marginal abatement cost among provinces, the marginal abatement cost savings from trading would occur for most China's provinces.

Key words: By-production approach; Data Envelopment Analysis; Directional Distance Function; Emission Trading System; Opportunity abatement cost; Marginal abatement cost

1 Introduction

In recent years, the ecological environment deterioration caused by global warming and climate change has not only affected the quality of life, but also has a profound impact on the sustainable development of

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human society and world economy. To solve these environmental problems, the United Nations has held some Climate Change Conferences to discuss countermeasures against these global environmental problems. Carbon emission permit trading, which is a market mechanism to reduce global greenhouse gas (GHG) emissions, has been considered an efficient and effective policy instrument in the mitigation of global warming and climate change (Demailly and Quirion, 2008; Li and Jia, 2016; Zhao et al., 2017).

Due to the rapid expansion of economy over the past decade, China has become the largest energy consumer and GHG emitter in the world (Wei et al., 2014). With increasing domestic resources and environmental constraints and the need of meeting international commitments for reducing GHG emissions, Chinese National Development and Reform Commission (NDRC) authorized seven administrative areas to launch pilot carbon emission trading system that started operation between 2013 or 2014. These even provinces and regions, at which are at different levels of industrial structure and economic development, includes Beijing, Chongqing, Tianjin, Shanghai, Shenzhen, Guangdong, and Hubei. More recently, a nationwide carbon emission permit trading schemes has established in the power industry sector by the end of 2017. However, China's nationwide carbon emission permit trading system is still in the experimental stage, and there are many problems existed, such as the defective in pricing mechanisms and low market participation (Peidong et al., 2009; Zhou et al., 2013). Therefore, understanding the impact of national carbon emission permit trading scheme on economy and social is critical (Lederer, 2012; Cui et al., 2014).

There are some literatures investigates the impact of national carbon emission permit trading scheme on economy from the perspective of improving the cost-effectiveness in CO_2 abatement. They answered the question that how much abatement costs savings can be identified by trading carbon emission permit. For example, Stavins (1995) first discussed the interaction between tradable emission permit and transaction costs from the theoretical perspective. Newell and Stavins (2003) predicted 51% abatement cost savings from trading nitrogen oxide emission permits with market-based policies in electric utilities industry of United States. Leleu (2012) introduced a hybrid theoretical model to ensure the correct sign of marginal abatement cost and the economic meaning of shadow price. Färe et al. (2014) employed the data envelopment analysis (DEA) model to calculate the difference of maximal kilowatt-hour between the command-and-control regulation and tradable emission permit regulation. Wang et al. (2016) also used a DEA-based programming model to estimate the recovery of GDP from trading carbon emission permit among provinces in China during 2006-2010.

In this study, we try to answer the question of how much the theoretical potential gains (or abatement cost savings) can be obtained from trading carbon emission permits in China's power industry sector among different provinces. We compare the carbon abatement cost from implementing two sequential simulations: no emission permit trading simulation and emission permit tradable simulation. On one hand, we employ a DEA-based by-production approach to estimate the opportunity abatement cost savings (i.e., the difference on maximal gross output value with and without carbon emission permit trading). Furthermore, CO_2 emission transfers among provinces and areas in trading are identified. DEA-based programming model, which can estimate the maximal economic output through a piecewise linear frontier, has been widely used in the research of tradable emission permits allocation that is viewed as the first step of starting the permit trading process (Lozano et al., 2009). On the other hand, we apply the parametric directional distance function (DDF) to compute the marginal abatement cost savings or the changes in shadow prices of CO_2.

This study makes some contributions to the existing literature from both the theoretical and the application perspectives. First, this study takes both the opportunity abatement cost and the marginal abatement cost into consideration, presenting a more comprehensive investigation on the economic benefit from trading carbon emission permit. Second, the opportunity abatement cost savings and the marginal abatement cost savings from carbon emission permit trading are derived from simulative calculations instead of econometric analysis which helps to avoid the impact of other policies and activities on changes of carbon abatement cost. Third, the DEA-based by-production approach provides a more reasonable evaluation for identifying the opportunity abatement cost savings from trading carbon emission permit in China's power industry with a residual generation mechanism setting. Fourth, this is the first study to estimate the abatement cost savings from nationwide carbon emission permit trading in China's power industry sector through an ex post analysis and to propose additional policy options for achieving more economic benefit.

The rest of this paper is structured as follows: Section 2 reviews the recent literature on modelling pollution-generating technologies and estimating the abatement cost of CO_2 emissions. Section 3 proposes the model for estimating opportunity abatement cost savings, and Section 4 presents the model for estimating marginal abatement cost savings. Section 5 presents the data. In Section 6, we report the empirical results and provide the discussions. Section 7 concludes this paper.

2 Literature review

2.1 Modelling pollution-generating technologies

Generally, the technologies on generating desirable outputs and pollutions has been formalized in four different ways. First, a kind of approaches consider pollutions as free disposable inputs (Yang and Pollitt, 2009; Mahlnerg et al., 2011; Wang et al., 2012). The main argument behind this kind of approach is that pollutions are unavoidable residuals and the subset of pollution-generating inputs. However, the free disposability assumption on pollutions includes the situation that finite amount inputs can generate infinite amount pollutions, thus violating the physical laws and the law of mass conservation (Färe and Grosskopf, 2003; Wang, Wei and Huang, 2018). Second, another group of approaches treats pollutions as extra outputs by assuming that pollutions satisfy weak disposability and desirable outputs and undesirable outputs satisfy null-jointness (Färe and Grosskopf, 2009; Shortall and Barnes, 2013; Song and Wang, 2018; Xian et al., 2018). This kind of approach assumes the joint-production of desirable outputs and pollutions. However, as discussed by Coelli et al. (2007) and Wang, Mi and Wei (2018), the weak disposability and null-jointness assumption would break the first law of thermodynamics. Third, due to the limit of the weak disposability assumption, a kind of approach based on the mass/energy balance equation was introduced (Lauwers et al., 1999; Førsund, 2018). Although this approach assumes the inevitability of generating pollutions, it ignores the correction between the pollution-generating inputs and non-pollution-generating inputs. Last, a more recent kind of approach divide the production progress into generating desirable outputs and generating pollutants, respectively (Førsund, 2009; Sueyoshi and Goto, 2010; Sueyoshi and Goto, 2013). The operational efficiency and environmental efficiency would be evaluated in different sub-frontier in this approach named by-production approach. Moreover, this model considers the interaction of pollution-generating inputs and non-pollution-generating inputs relying the cost disposability assumption in the technology with respect to pollutions.

2.2 Estimating abatement cost for CO_2

The question of the estimation of the economic cost arising from pollution generation has become an important area of the interest in energy and environment. On the one hand, the opportunity abatement cost of CO_2 represents the economic benefits of the trade-off between generating CO_2 emissions and desirable outputs. It can be computed through different pollution-generating technologies. On the other hand, the shadow price of CO_2, which refers to the opportunity cost caused by an additional unit in terms of CO_2 emission reduction, can be viewed as one kind of marginal abatement cost. The shadow price of CO_2 is derived from the available market prices of desirable outputs through duality theory and distance function (or directional distance function), and the distance function (or directional distance function) could be estimated by nonparametric or parametric approaches (Zhou et al., 2014). The parametric economic models need the specification of production function form, and the nonparametric mathematical programing methods offer larger possibilities because of less restrictive assumption.

The nonparametric methods without a predefining function form (e.g., data envelopment analysis, DEA), have been widely used to estimate the environmental efficiency and the shadow prices of CO_2. For example, Boyd et al. (1996) utilized DEA technique to estimate the production frontier and the marginal abatement cost of SO_2 for the coal-burning utilities of United States. Lee et al. (2014) integrated the engineering-economic approach and the nonparametric directional distance function to estimate the shadow price of CO_2 in the power plants of Korean. In addition, Lee and Zhou (2015) conducted a directional marginal productivity approach to estimate the directional shadow prices of CO_2, SO_2 and NOx in the coal power industry of United States.

The parametric methods are more commonly used in application because the production function with a specific form is differentiable everywhere (Du et al., 2015). For example, Färe et al. (1993) first used a translog distance function to estimate the shadow prices for four pollutants of pulp and paper mills industry in Michigan and Wisconsin. Harkness (2006) also employed the translog functional form of DDF to estimate the shadow prices of CO_2 for the electric utility industry of US. Marklund and Samakovlis (2007) used the parametric DDF to estimate the marginal abatement cost of CO_2 emissions for EU member states during

1990-2000. Moreover, Liu et al. (2016) utilized a combined model with dynamic simulation model, modified Trans-log production function and multi-objective linear programming to evaluate the impact on the CO_2 abatement cost of power generation sector in China.

3 Opportunity abatement cost estimation method

3.1 Opportunity abatement cost

To qualify the generation of pollutions in the production process, joint production is commonly used for analysis. However, the joint production, which considers pollution as input with free disposability assumption or as output with weak disposability assumption, may lead to unacceptable implications for the trade-offs between inputs and outputs. In the other words, these treating indicates that there would be a "rich menu" of output vector in the production possibility set, possibly including some zero amounts of outputs given the fixed inputs (Dapko et al., 2016). To solve this problem, the by-production approach accounts for the materials balance principles implying the inevitability of a certain quantity of incidental output, given the certain amounts of inputs and/or desirable outputs.

In this study, by-production model based on DEA technique is employed to estimate the opportunity abatement cost, as it is appropriate to obtain the abatement cost with multiple inputs and outputs from the perspective of distinguishing the sub-processes of producing desirable outputs and pollutions. By utilizing the provincial data of China's power industry sector for the 2011-2015 period, the maximal potential desirable output (i.e., gross industrial output value) is estimated under conditions without and with carbon emission permit trading, respectively. The distinguish in the maximal potential gross industrial output value between non-tradable and tradable is used to explain opportunity abatement cost savings from trading carbon emission permit.

The by-production model, proposed by Murty et al. (2012), and generalized by Dakpo (2015) and Dapko et al. (2017), appears to be a promising approach in the modelling of pollution generation technologies. In this approach, two sub-processes are estimated: a desirable output production technology and a residual pollutions generation technology. Assuming each province employs three inputs (x_i, i =1, 2, 3) including the number of employees, net value of fixed assets and energy consumption, to generate one desirable output of gross industrial output value, denoted by y, and one undesirable output of CO_2 emissions, denoted by u, over t=1,…,5 years. The input vector can be divided into two sub-vectors: the non-pollution-causing inputs X_1 (i.e., net value of fixed assets and the number of employees) and the pollution-causing input x_3 (i.e., energy use). Hence, the total production technology T can be represented by:

$$T = T_1 \cap T_2 \qquad (1)$$

with

$$T_1=\left[\left(X_1,x_3,y,u\right)\in \boldsymbol{R}_+ \middle| f\left(X_1,x_3,y\right)\le 0\right] \quad (2)$$

$$T_2=\left[\left(X_1,x_3,y,u\right)\in \boldsymbol{R}_+ \middle| u\ge g\left(x_3\right)\right] \quad (3)$$

where f and g are differentiable and continuously. The overall production possibility set T represents a pollution-generating technology setting a residual generation mechanism with material balance. Set T_1 is a standard production technology set, reflecting the production in which inputs can be transformed into desirable output and undesirable output. In this set, the inputs, desirable output satisfy strongly disposable assumption and undesirable output imposes no constraint. Moreover, set T_2 reflects the nature's residual-generation mechanism. The equality constraint $u=g\left(x_3\right)$ in T_2 represents the material balance, implying that given the quantity of pollution-causing input, the level of pollution is fixed. In this set, pollution satisfies costly disposable assumption as follows:

$$\left(X_1,x_3,y,u\right)\in T\wedge \bar{u}\ge u\wedge \bar{x}_3\le x_3\Rightarrow\left(X_1,\bar{x}_3,y,\bar{u}\right)\in T \quad (4)$$

The costly disposable assumption indicates the possibility of inefficiency in the production of pollution. In summary, this technology is modeled as an intersection of two processes (i.e., an intended production technology and a nature's residual-generation set). The former satisfies standard disposability properties, while the latter violates strong disposability of pollution and pollution-causing inputs. As a result, the intersection also violates standard free disposability of pollution and pollution causing inputs.

As discussed before, the abatement cost saving is defined as the gap between potential maximal gross industrial output value with carbon emission permit trading and without (Brännlund et al., 1998; Färe et al., 2013). First, we create a no trading simulation model for all provinces in each t period. For province j_0 at t period, its potential maximal gross industrial output value with no carbon emission permit trading can be estimated as follows:

$$\begin{aligned} &Y_{j_0}^t=\max_{\lambda_j,\omega_j,\theta}\ \theta y_{j_0}\\ &s.t.\quad x_{1j_0}\ge\sum_{j=1}^n x_{1j}\lambda_j,\ x_{2j_0}\ge\sum_{j=1}^n x_{2j}\lambda_j,\ x_{3j_0}\ge\sum_{j=1}^n x_{3j}\lambda_j,\\ &\qquad \theta y_{j_0}\le\sum_{j=1}^n y_j\lambda_j,\ x_{3j_0}\le\sum_{j=1}^n x_{3j}\omega_j,\ u_{j_0}\ge\sum_{j=1}^n u_j\omega_j, \qquad (5)\\ &\qquad \sum_{j=1}^n x_{3j}\lambda_j=\sum_{j=1}^n x_{3j}\omega_j,\ \sum_{j=1}^n\lambda_j=1,\ \sum_{j=1}^n\omega_j=1,\\ &\qquad \lambda_j,\omega_j\ge 0,\ \ j=1,2,\ldots,n. \end{aligned}$$

Here, λ_j and ω_j are intensity variables and nonnegative; θ is the increased proportion of gross industrial output value. The technology of desirable output and pollution both assume variable returns to scale (VRS), i.e., a proportional change in inputs would not induce a similar proportional change in desirable output and pollution. The last equality connects two sub-progresses of generating desirable output and undesirable output.

Thus, the corresponding maximal gross industrial output value for all provinces at *t* period and the total maximal gross industrial output value for all provinces over the entire study period can be calculated as follows, respectively:

$$Y^t = \sum_{j_0=1}^{n} Y_{j_0}^t, \ t=1,2,...,T. \qquad (6)$$

$$Y^{NT} = \sum_{t=1}^{T} Y^t. \qquad (7)$$

where the superscript *NT* refers to no carbon emission permit trading.

Similarly, given that the carbon emission permit can be reallocated among different provinces and be allowed for interspatial and intertemporal trading (i.e., the nationwide emission permit trading), the maximal gross industrial output value for all provinces at the whole *T* periods can be computed as follows:

$$\begin{aligned}
&\max_{\lambda_{jk}^t, \omega_{jk}^t, \theta_k^t, \delta_k^t} \ Y^{IIT} = \sum_{t=1}^{T}\sum_{k=1}^{n} \theta_k^t y_k^t \\
&s.t. \ \ x_{1k}^t \ge \sum_{j=1}^{n} x_{1j}^t \lambda_{jk}^t, \ x_{2k}^t \ge \sum_{j=1}^{n} x_{2j}^t \lambda_{jk}^t, \ x_{3k}^t \ge \sum_{j=1}^{n} x_{3j}^t \lambda_{jk}^t, \\
&\quad \theta_k^t y_k^t \le \sum_{j=1}^{n} y_j^t \lambda_{jk}^t, \ x_{3k}^t \le \sum_{j=1}^{n} x_{3j}^t \omega_{jk}^t, \ \delta_k^t u_k^t \ge \sum_{j=1}^{n} u_j^t \omega_{jk}^t, \\
&\quad \sum_{j=1}^{n} \omega_{jk}^t = 1, \ \sum_{j=1}^{n} \lambda_{jk}^t = 1, \ \sum_{j=1}^{n} x_{3j}^t \lambda_{jk}^t = \sum_{j=1}^{n} x_{3j}^t \omega_{jk}^t, \\
&\quad \textit{Aggregate bad output}: \sum_{t=1}^{T}\sum_{k=1}^{n} \delta_k^t u_k^t \le \sum_{t=1}^{T}\sum_{k=1}^{n} u_k^t, \\
&\quad \lambda_{jk}^t, \omega_{jk}^t \ge 0, \ j=1,2,...,n, \ k=1,2,...,n, \ t=1,2,...,T.
\end{aligned} \qquad (8)$$

In model (8), λ_j^t and ω_j^t are same as those in model (3), and δ_k^t is the change proportion of CO_2 emissions. Consequently, $U^{IIT} = \sum_{t=1}^{T}\sum_{k=1}^{n} \delta_k^t u_k^t$ represents the total reallocated carbon emission permit over the entire *T* period and superscript *IIT* refers to the interspatial and intertemporal trading simulation. The restriction for aggregate bad output means that total reallocated CO_2 emission permit could not exceed the amount of total observed CO_2 emissions.

3.2 Opportunity abatement cost savings

Firstly, $Y=\sum_{t=1}^{T}\sum_{j=1}^{n}y_j^t$ is the observed industrial gross output value. After calculated model (5), Eq. (6) and (7) the maximal industrial gross output value Y^{NT} is the opportunity abatement cost when technical inefficiency is eliminated. If the calculated industrial gross output value is larger than the observed one, it implies that technical inefficiency exists for this province under estimation. Consequently, opportunity abatement cost savings from removing technical inefficiency could be defined as the difference between the optimized industrial gross output value without trading and observed gross output value, i.e., $CS_1=Y^{NT}-Y$.

Secondly, the introduction of an interspatial and intertemporal carbon emission permit trading scheme is simulated in model (12). Thus, the opportunity abatement cost savings from trading, which denotes the impact of trading CO_2 emissions, can be defined as the difference between the optimized industrial gross output value without and with trading, i.e., $CS_2=Y^{IIT}-Y^{NT}$. $CS_2 > 0$ implies trading carbon emission permit among multi-regions is conducive to saving opportunity abatement cost.

4 Marginal abatement cost estimation method

The estimation of the shadow price of pollutants is carried out following the approach of Färe et al. (2006), which is based on the parametric directional distance function (DDF). Hence, we first introduce the DDF and then derive the shadow price.

First, the production technology is represented by the output sets $\boldsymbol{P}(x)$ (Molinos-Senante et al., 2016), where:

$$\boldsymbol{P}(\boldsymbol{x})=\{(y,u):\boldsymbol{x}\ can\ produce\ (y,u)\},\ \boldsymbol{x}\in\boldsymbol{R}_+^m. \qquad (9)$$

Then, the directional output distance function reflects the production technology and can defined as follows (Chung et al., 1997):

$$\vec{\boldsymbol{D}}(\boldsymbol{x},y,u;\vec{\boldsymbol{g}})=max\{\beta:(\boldsymbol{x},\boldsymbol{y}+\beta\vec{g}_y,\boldsymbol{u}-\beta\vec{g}_{\boldsymbol{u}})\in\boldsymbol{P}(\boldsymbol{x})\}. \qquad (10)$$

where $\vec{\boldsymbol{g}}=(\vec{g}_y,-\vec{g}_u)$ is the output directional vector and is always positive. This DDF simultaneously contracts u and expands y along the $\vec{\boldsymbol{g}}$ direction until it hits the boundary of $\boldsymbol{P}(\boldsymbol{x})$. The distance β is the inefficiency score and is nonnegative ($\beta\geq 0$).

According to Bellenger and Herlihy (2010), the DDF inherits some properties from the possibility set $\boldsymbol{P}(\boldsymbol{x})$, these properties include:

i) $\vec{\boldsymbol{D}}(\boldsymbol{x},y,u;\vec{\boldsymbol{g}})\geq 0$.

ii) $\vec{\boldsymbol{D}}\left(\boldsymbol{x}, y+\partial\vec{g}_y, u-\partial\vec{g}_{\boldsymbol{u}};\vec{\boldsymbol{g}}\right)=\vec{\boldsymbol{D}}\left(\boldsymbol{x}, y, u;\vec{\boldsymbol{g}}\right)-\partial$.

iii) $\vec{\boldsymbol{D}}\left(\boldsymbol{x}, y', u;\vec{\boldsymbol{g}}\right)\geq\vec{\boldsymbol{D}}\left(\boldsymbol{x}, y, u;\vec{\boldsymbol{g}}\right)$ for $\left(y', u\right)\leq\left(y, u\right)\in\boldsymbol{P}(\boldsymbol{x})$.

iv) $\vec{\boldsymbol{D}}\left(\boldsymbol{x}, y, u';\vec{\boldsymbol{g}}\right)\leq\vec{\boldsymbol{D}}\left(\boldsymbol{x}, y, u;\vec{\boldsymbol{g}}\right)$ for $\left(y, u'\right)\leq\left(y, u\right)\in\boldsymbol{P}(\boldsymbol{x})$.

v) $\vec{\boldsymbol{D}}\left(\boldsymbol{x}, \theta y, \theta u;\vec{\boldsymbol{g}}\right)\geq 0$ for $\left(y, u\right)\in\boldsymbol{P}(\boldsymbol{x})$ and $0\leq\theta\leq 1$.

Property (i) is the representation property, states that the DDF is nonnegative for all feasible output vectors. Property (ii) refers to translation property, meaning that if undesirable outputs are contracted by $\vec{g}_u$ and desirable outputs are expanded by $\vec{g}_y$, the value of the resulting DDF will be more efficient by a positive scalar ∂ . Property (iii) is the non-increasing monotonicity property referring to the strong disposability assumption of desirable outputs. In addition, property (iv) is the non-decreasing monotonicity property corresponding to undesirable outputs. Lastly, property (v) represents the weak disposability assumption of desirable and undesirable outputs.

For empirical estimation of DDF, both parametric approach and nonparametric approach can be used. In this study, the parametric linear programming (LP) approach is employed because this approach has the advantages of constraints inclusion and differentiability. In addition, the quadratic functional form of DDF satisfies the translation property and is twice differentiable and flexible (Wei et al., 2013). Therefore, a quadratic functional form is assumed for the *j*th unit as follows:

$$\vec{D}\left(x_j, y_j, u_j;\vec{\boldsymbol{g}}\right)$$
$$=\alpha+\sum_{i=1}^{m}\alpha_i x_{ij}+\beta_1 y_j+\gamma_1 u_j+\frac{1}{2}\sum_{i=1}^{m}\sum_{i'=1}^{m}\alpha_{ii'}x_{ij}x_{i'j}+\beta_2 y_j^{\ 2}+\gamma_2 u_j^{\ 2}+\sum_{i=1}^{m}\delta_i x_{ij}y_j+\sum_{i=1}^{m}\eta_i x_{ij}u_j+\mu y_j u_j . \tag{11}$$

Additionally, we assume that the directional vector $\vec{\boldsymbol{g}}=\left(\vec{g}_y, -\vec{g}_u\right)$ = (0, 1) and (1, -1). Such assumption are in line with the no trade simulation model and tradable simulation model respectively. Specifically, $\vec{\boldsymbol{g}}$ = (0, 1) means that we hope to an extend on desirable output when undesirable output is unchanged, and $\vec{\boldsymbol{g}}$ = (1, -1) means that we hope to an extend on desirable output and an reduction on undesirable output simultaneously.

The deterministic LP algorithm proposed by Lee and Zhou (2015) and Molinos-Senante (2015) can be used to estimate the parameters of the quadratic DDF represented in Eq. (11), and can be represented as follows:

$$
\begin{aligned}
&\min_{\lambda_j,\tilde{y}} \ \sum_{j=1}^{n}\left[\vec{D}\left(\bar{x}_j,\bar{y}_j,\bar{u}_j;\vec{\boldsymbol{g}}\right)-0\right],\\
&s.t.\ \ (i)\ \vec{D}\left(\bar{x}_j,\bar{y}_j,\bar{u}_j;\vec{\boldsymbol{g}}\right)\geq 0,\ j=1,\ldots,n,\\
&\qquad (ii)\,\partial\vec{D}\left(\bar{x}_j,\bar{y}_j,\bar{u}_j;\vec{\boldsymbol{g}}\right)\big/\partial x_i\geq 0,\ i=1,\ldots,m,\\
&\qquad (iii)\,\partial\vec{D}\left(\bar{x}_j,\bar{y}_j,\bar{u}_j;\vec{\boldsymbol{g}}\right)\big/\partial y\leq 0,\\
&\qquad (iv)\,\partial\vec{D}\left(\bar{x}_j,\bar{y}_j,\bar{u}_j;\vec{\boldsymbol{g}}\right)\big/\partial u\geq 0,\\
&\qquad (v)\ \ \alpha_{ii'}=\alpha_{i'i}, i\neq i',\\
&\qquad (vi)\,\beta_2\vec{g}_y-\mu\vec{g}_u=0, \beta_1\vec{g}_y-\gamma_1\vec{g}_u=-1,\\
&\qquad\quad \mu\vec{g}_u-\gamma_2\vec{g}_u=0, \delta_i\vec{g}_y-\eta_i\vec{g}_u=0,\ i=1,2,\ldots,m.
\end{aligned}
\tag{12}
$$

To overcome the convergence problem, the normalized values $\bar{x}_j$, $\bar{y}_j$, and $\bar{u}_j$ are utilized here. This model minimizes the sum of the gaps between the observed unit and that of its corresponding projection unit on the production frontier. In model (12), restriction (*i*) reflects the representation property of DDF, guaranteeing that the production processes for all of the provinces are feasible. Inequalities (*ii*)-(*iv*) are the monotonicity property of inputs, desirable outputs and undesirable outputs, respectively. These three sets of restrictions are employed to guarantee the signs of the shadow prices. Additionally, inequality (*v*) represents the symmetry property of DDF, whereas equalities (*vi*) represents the translation properties.

Based on the estimated parameters in model (12), the shadow price of the pollutions can be written as follows:

$$
q=p\times\left(\frac{\partial\vec{D}\left(\bar{x},\bar{y},\bar{u};\vec{\boldsymbol{g}}\right)/\partial u}{\partial\vec{D}\left(\bar{x},\bar{y},\bar{u};\vec{\boldsymbol{g}}\right)/\partial y}\right)\times\frac{mean\ y}{mean\ u}. \tag{13}
$$

where *p* is the price of desirable output and can be obtained in advance. Since the values of inputs and outputs are normalized by dividing their mean values in model (12), the shadow prices should also multiply the mean value of the ratio of *y* by *u*.

We compute both the relative shadow prices of pollution using the observed values, the optimal values with and without trading carbon emission permit. If the relative shadow price under the no trading simulation model is lower than the relative shadow price of the observed values, their difference would be defined as the marginal abatement cost savings from eliminating technical inefficiency in this study. Similarly, if the relative shadow price with trading is lower than the relative shadow price without trading, their difference would be defined as the marginal abatement cost savings from trading carbon emission permit.

5 Results and discussion

5.1 Data and descriptive statistics

This study is conducted to analyze the economic benefit (i.e., cost savings) from trading CO_2 emission permit between 30 provinces in China's power industry sector over 2011 - 2015 using the models developed in

Section 3 and 4. Therefore, the observed CO_2 emissions and economic output (i.e., gross industrial output value at provincial level) are selected as outputs. To generate the economic output, three important inputs (i.e., labor, capital and energy use) are taken into consideration. All the results are calculated in The General Algebraic Modeling System (GAMS) software.

We collect the data for labor (i.e., number of employees), capital (i.e., net value of fixed assets) and intended output (i.e., gross industrial output value) from the *China Industry Economy Statistical Yearbook* 2012 - 2016. The data for energy use is obtained from the *China's Energy Statistical Yearbook* 2012 - 2016, and the amount of fuel consumption is calculated in million ton of coal equivalent (ce). The data for CO_2 emissions are retrieved from the apparent fuel consumption using the conversion factors of Intergovernmental Panel on Climate Change (IPCC) Guidelines. The specific equation is $CE_i = ET_i \times f_i$, where CE_i is CO_2 emissions from i_{th} energy type, ET_i is the amount of i_{th} fossil fuels measured in physical units, and f_i is the corresponding CO_2 emission factor of fossil energy. Thus, the total CO_2 emissions CE can be calculated as $CE = \sum_i CE_i$. Table 1 presents the descriptive statistics of inputs and outputs at the regional level.

Table 1 Descriptive statistics of inputs and outputs

Input and output	Units	Mean	St. Dev.	Minimum	Maximum
Number of employees	Thousand persons	92.8	50.5	9.2	212.3
Net value of fixed assets	Billion yuan	206.7	119.4	18.3	597.6
Energy consumption	Million ton of ce	52.0	32.5	4.9	140.0
Gross industrial output value	Billion yuan	181.4	135.3	9.5	640.5
CO_2 emissions	Million tons	130.5	101.3	4.6	417.7

5.2 Potential opportunity abatement cost savings from trading

Model (5) and Model (8) are first employed to maximal gross values with and without implementing emission permit trading system, and thus identifying potential opportunity abatement cost savings.

Table 2 reports the potential opportunity abatement cost savings at the national level during 2011-2015. The column of potential abatement cost savings from eliminating technical inefficiency indicates the difference between the optimal gross output value of no trading simulation model and the observed industrial gross output value, and the column of potential abatement cost savings from introducing trading represents the difference between the optimal gross output value with and without carbon emission permit trading. It can be seen that 2305 billion yuan (42.4%) annual average potential abatement cost would be saved after removing technical inefficiency in China's power generation sector during entire 12th Five-Year period, whereas more 1024 billion yuan (13.2%) annual average potential abatement cost would be identified after introducing a nationwide carbon emission permit trading system. To be specific, the increased annual percentage of potential cost savings from eliminating technical inefficiency ranges from 36% to 52% during 2011–2015 which represents a considerable amount of theoretical loss of gross output value associated with technical inefficiency in power industry sector of China. In other words, the reason of theoretical loss of gross output value here is that not all provinces are operating on the efficient production frontier. During the same period, the potential cost savings from trading, which indicate the differences in maximal gross output value with and without the tradable permit system estimations in China's power generation sector, makes the impact of national carbon emission permit trading system on the industrial gross output value quantified. The increased annual percentage of potential cost savings from trading ranges from 3.8% to 18.2%, which indicate the theoretical magnitude of gross output value loss associated with the temporal regulatory rigidity and the spatial temporal regulatory rigidity of China's power generation sector. Scilicet, the theoretical gross output value losses here are caused by the suboptimal allocation of emission permit among provinces and years.

Table 2 Potential opportunity abatement cost savings

Year	Potential cost savings (Billion yuan)		Percentage of potential cost savings	
	From eliminating inefficiency	From trading	From eliminating inefficiency	From trading
2011	1696	1163	36.0%	18.2%
2012	1877	1198	36.7%	17.2%
2013	2940	323	52.0%	3.8%
2014	2376	1180	41.1%	14.5%
2015	2634	1257	44.3%	14.6%
Average	**2305**	**1024**	**42.4%**	**13.2%**

In details, Fig. 1 shows the potential opportunity abatement cost savings form trading for each province during entire 12th Five-Year period. From Fig. 1, it can be seen that Xinjiang has the highest total abatement costs savings about 351 billion yuan in economic gross output value loss occurred with trading CO_2 emission permit, followed by Henan as the second highest. Mover, Xinjiang not only has the highest abatement costs savings from trading, it also is subject to much higher increased percentage accounting for around 46.7%. On the contrary, Hainan has the smallest abatement costs savings and has nearly 27% of increased percentage after the CO_2 emission permits are reallocated. The underlying reason is that Hainan has the relatively small production scale on electricity generation and energy consumption compared with the other regions, and thus limited economic scale might occur with limited amount on economic loss recovery. In addition, it is worth mentioning that Qinghai has the greatest increase percentage associate with trading carbon emission permit. The possible reason is that although Qinghai has similar production scale with Hainan, more capital capacity would occur with more potentials on recovering industrial gross output value.

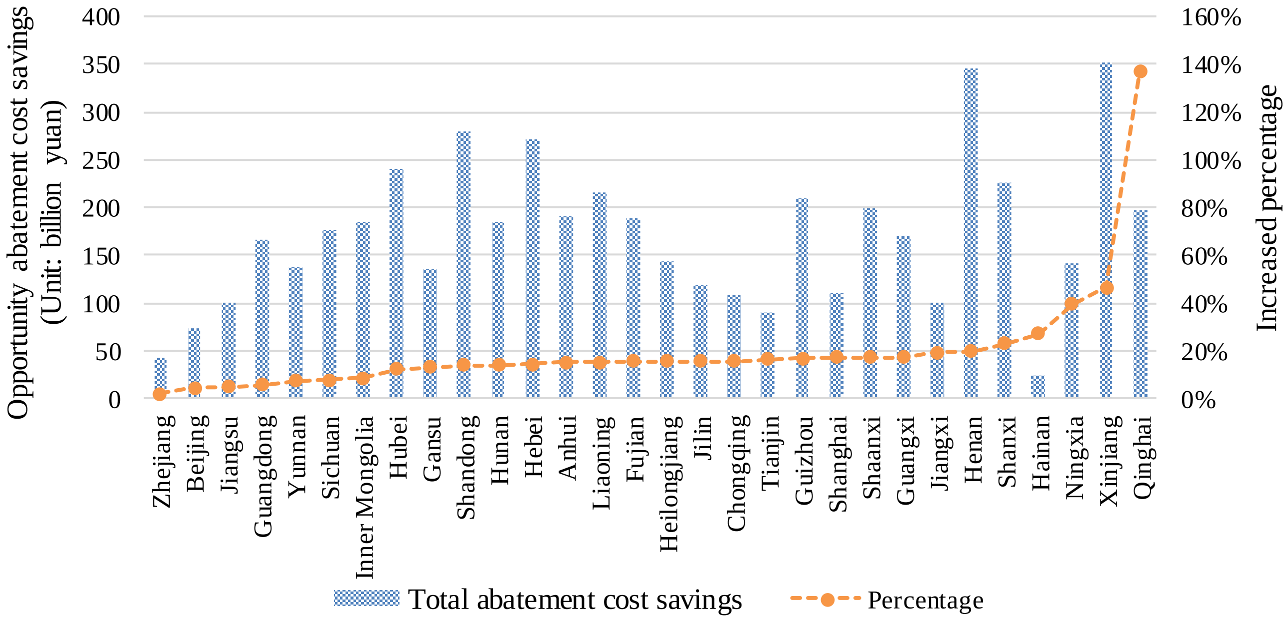

Fig. 1 Potential opportunity abatement cost savings from trading for each province

5.3 CO_2 emission permit transfers in trading

As demonstrated earlier, CO_2 emission permit would be reallocated among provinces after introducing an interspatial and intertemporal carbon emission trading system in the power industry sector of China. Thus, in this sub-section, we analyze the CO_2 emission permit transfers among regions after trading. Fig. 2 depicts the specific CO_2 emission permit transfers during 2011-2015.

It shows that the CO_2 emission permit mainly transfer from east area to west area and from north area to south area, indicating that the southwest area of China with low carbon inefficiency and low abatement cost need to buy additional carbon emission permits from the northeast area and northwest area with high carbon inefficiency and high emission abatement cost. It is worth noting that there are two exceptions: Beijing and Jiangsu provinces. These two regions are also efficient units with low carbon inefficiency and low emission abatement costs, and thus, they would emit more CO_2 emissions than their observed values and buy additional carbon emission permits to obtain more regionally industrial gross output value.

Fig. 2 CO_2 emission permit transfers during 12th Five-Year period

5.4 Potential marginal abatement cost savings from trading

By using Model (12) and Eq. (13) described in section 4, the relative shadow prices of CO_2 emissions for each province are estimated. Table 3 presents the shadow prices of CO_2 and summarizes the situation of marginal abatement cost savings for each province. The O column represents the relative shadow prices calculated by the observed values. The NT column represents the relative shadow prices computed by the optimal values without trading carbon emission permit, that is, the marginal abatement cost for CO_2 after eliminating technical inefficiency. The T column represents the relative shadow prices computed by the optimal values with trading, that is, the marginal abatement cost for CO_2 after introducing an interspatial and intertemporal emission permit trading system. Moreover, the hook and cross indicate the situation that marginal abatement cost savings exist and not exist, respectively.

In Table 3, the shadow prices of CO_2 among provinces shows significant difference, ranging from 0.15 Yuan/ton to 1285 Yuan/ton in the O scenario, from 0.03 Yuan/ton to 201 Yuan/ton in the NT scenario, and from 5 Yuan/ton to 65 Yuan/ton in the T scenario. There are two reasons for the gap on the shadow prices of CO_2 among provinces. One reason is the production heterogeneity on electricity generation among provinces. For example, there are average 22% fossil fuel consumption in total energy consumption for electricity generation in Yunnan and Qinghai during 2011-2015, whereas there are over 99% fossil fuel consumption in total energy consumption for electricity generation in Tianjin and Shanghai. The difference in the energy structure for electricity generation will directly lead to the difference in CO_2 emissions. Another reason is that these shadow prices are derived from different simulation scenarios with differentiated simulation assumptions. Furthermore, the average shadow price of CO_2 emissions calculated by the observed values is the highest associated with both two directions and followed by the average shadow price of CO_2 emissions without trading and with trading. Therefore, it could be concluded that although not all provinces could be identified marginal abatement cost savings after removing technical inefficiency or introducing carbon emission permit trading system, the marginal abatement cost savings would occur at the national level. In specific, there are almost 47 and 39 yuan/ton marginal abatement cost savings under direction (1,0) and (1,1), respectively.

Table 3 The shadow prices of CO_2 emissions during 2011-2015 (unit: Yuan/ton)

			(1,0)					(1,1)		
	O	NT	NT	T	T	O	NT	NT	T	T
Average	**192**	**77**	**-**	**30**	**-**	**397**	**69**	**-**	**30**	**-**
Beijing	176	65	√	65	×	565	165	√	21	√
Tianjin	58	65	×	30	√	355	16	√	18	×
Hebei	303	117	√	41	√	200	55	√	46	√
Shanxi	159	0.03	√	17	×	130	4	√	12	×
Inner Mongolia	0.15	151	×	30	√	204	12	√	19	×
Liaoning	126	94	√	44	√	236	15	√	37	×
Jilin	94	55	√	21	√	370	26	√	44	×
Heilongjiang	119	57	√	15	√	327	31	√	58	×
Shanghai	50	3	√	23	×	401	86	√	5	√
Jiangsu	1028	58	√	11	√	226	127	√	6	√
Zhejiang	526	201	√	43	√	212	84	√	17	√
Anhui	219	119	√	37	√	202	22	√	28	×
Fujian	159	112	√	40	√	323	51	√	22	√
Jiangxi	145	49	√	10	√	305	16	√	44	×
Shandong	549	71	√	23	√	122	28	√	52	×
Henan	377	110	√	33	√	166	33	√	59	×
Hubei	71	130	×	51	√	803	172	√	29	√
Hunan	119	84	√	37	√	472	72	√	43	√
Guangdong	744	0.03	√	17	×	538	332	√	44	√
Guangxi	131	76	√	24	√	422	57	√	47	√
Hainan	42	49	×	18	√	389	0.02	√	16	×
Chongqing	55	67	×	32	√	442	28	√	25	√
Sichuan	104	72	√	21	√	1285	274	√	36	√
Guizhou	124	95	√	35	√	351	42	√	39	√
Yunnan	0.34	107	×	38	√	904	159	√	13	√
Shaanxi	102	97	√	36	√	315	28	√	34	×
Gansu	56	91	×	37	√	435	40	√	28	√
Qinghai	4	3	√	16	×	609	65	√	10	√
Ningxia	57	45	√	17	√	270	3	√	15	×
Xinjiang	68	74	×	28	√	333	20	√	21	×

Note: O - the shadow prices of the observed value; NT - the shadow prices of the optimal value without trading carbon emission permit; T - the shadow prices of the optimal value with trading; √ - the marginal abatement cost savings exits; × - there is no marginal abatement cost savings.

6 Conclusions

After recent five years' preparation, China's seven pilots carbon emission permit trading systems have officially launched since 2013 and 2014 and a nationwide carbon emission permit trading system has established in the power industry sector by the end of 2017. Through an ex post analysis based on China's provincial data for power industry sector over 2011-2015, this study attempts to estimate abatement cost savings from trading permits. On the one hand, the by-production approach based on nonparametric DEA model is utilized to estimate opportunity abatement cost savings from trading carbon emission permit and analyze CO_2 emission transfer among regions. On the other hand, a parametric directional distance function is applied to further estimate the change in shadow prices of CO_2 (i.e., marginal abatement cost savings).

The main findings from our research are summarized as follows:

i. There would be approximately 42% and 13% potential opportunity abatement cost savings from removing technical inefficiency and cross-industrial trading regulatory rigidity. Specifically, 2,305-billion-yuan annual average loss of gross output value would be recovered when technical inefficiency is eliminated, and 1,024-billion-yuan annual average loss of gross output value due to sub-optimal allocation of CO_2 emissions among provinces would be identified during 2011-2015.

ii. Xinjiang and Henan, which could realize almost 350 billion yuan in economic gross output value loss with trading CO_2 emission permit, show the largest potential opportunity abatement cost savings. In addition, Qinghai, which could achieve over 100% economic gross output value recovery, shows the highest percentage increase in opportunity abatement cost savings.

iii. In the interspatial and intertemporal trading simulation, the CO_2 emission permit would be mainly transferred from east area to west area and from north area to south area in China's electricity generation industry.

iv. The relative shadow prices of CO_2 emissions ranges from 0.15 yuan to 1,285 Yuan per ton of CO_2 in the observed value scenario, from 0.03 yuan to 201 yuan per ton of CO_2 in the non-trading simulation scenario, and from 5 yuan to 65 yuan in the trading simulation scenario. Although the marginal abatement cost savings would not exist in all provinces, it would be identified through not only removing technical inefficiency but also introducing carbon emission permit trading system at the national level.

v. At the national level, there are 47 and 39 yuan/ton marginal abatement cost savings under direction (1,0) and (1,1), respectively.

Based on the results and conclusions, several important policy implications could be drawn as follows:

i. CO_2 emission permit trading system should be encouraged in China's power industry sector. As shown in Section 6, our results provide strong evidence that there would be a certain potential opportunity abatement cost savings and potential marginal abatement cost savings in the nationwide carbon emission permit trading scheme of China's power industry. Therefore, further improving the permit trading schemes in China's power industry sector may help realize these abatement cost savings and emission reduction potentials.

ii. CO_2 emission permit trading system should be also encouraged in other industry sectors of China. Except for power industry sector, there are other industry sectors with high energy consumption and high carbon emissions such as Smelting and Pressing of Ferrous Metals industry sector. Hence, the nationwide CO_2 emission permit trading system will be helpful for saving abatement cost and controlling carbon emissions.

iii. While allocating CO_2 emission permit, one suggestion to the policy-makers is that not only the potential CO_2 emission reduction should be considered, but also the economic growth (or the potential of industrial value added) should be involved in.

iv. The policies on eliminating technical inefficiency should be improved in China's power industry sector.

v. Our results show that the marginal abatement cost of CO_2 shows significantly different among provinces, and thus, the initial allocation and initial price of carbon emission permit might be various among different provinces.

With the establishment of the nationwide carbon emission permit trading system, more and more industry sectors would be covered. Thus, future research would take into consideration of more industry sectors when understanding the impact of national carbon emission permit trading scheme on economic growth and social development.

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References

Bellenger MJ, Herlihy AT. Performance-based environmental index weights: are all metrics created equal? Ecol Econ 2010;69(5):1043-1050. https://doi.org/10.1016/j.ecolecon.2009.11.021.

Boyd G, Molburg J, Prince R. Alternative methods of marginal abatement cost estimation: non-parametric distance function. Proceedings of the USAEE/IAEE 17th Conference. 1996;86–95. Available at: < https://www.osti.gov/biblio/449842> [accessed July 2018].

Brännlund R, Chung Y, Färe R, Grosskopf S. Emissions trading and profitability: the Swedish pulp and paper industry. Environ. Resour Econ 1998;12 (3):345-356. https://doi.org/10.1023/A:1008285813997.

Chung YH., Färe R, Grosskopf S. Productivity and undesirable outputs: a directional distance function approach. J Environ Manage 1997;51(3):229-240. https://doi.org/10.1006/jema.1997.0146.

Coelli T, Lauwers L, VanHuylenbroeck G. Environmental efficiency measurement and the materials balance condition. J Prod Anal 2007;28:3-12. https://doi.org/10.1007/s11123-007-0052-8.

Cui LB, Fan Y, Zhu L, Bi QH. How will the emissions trading scheme save cost for achieving China's 2020 carbon intensity reduction target? Appl Energy 2014;136:1043-1052. https://doi.org/10.1016/j.apenergy.2014.05.021.

Dakpo HK. On modeling pollution-generating technologies: a new formulation of the by-production approach. EAAE PhD Workshop. Rome, Italy; 2015. Available at: <https://ageconsearch.umn.edu/bitstream/245191/2/wp16-06.pdf> [accessed July 2018].

Dakpo KH, Jeanneaux P, Latruffe L. Modelling pollution-generating technologies in performance benchmarking: Recent developments, limits and future prospects in the nonparametric framework. Eur J Oper Res 2016;250(2): 347-359. http://dx.doi.org/10.1016/j.ejor.2015.07.024.

Dakpo KH, Jeanneaux P, Latruffe L. Greenhouse gas emissions and efficiency in French sheep meat farming: A non-parametric framework of pollution-adjusted technologies. Eur Rev Agr Econ 2017;44(1):33-65. https://doi.org/10.1093/erae/jbw013.

Demailly D, Quirion P. European emission trading scheme and competitive-ness: a case study on the iron and steel industry. Energy Econ 2008;30(4):2009-2027. https://doi.org/10.1016/j.eneco.2007.01.020.

Du L, Hanley A, Wei C. Marginal abatement costs of carbon dioxide emissions in China: a parametric analysis. Environ Resource Econ 2015;61(2):191-216. https://doi.org/10.1007/s10640-014-9789-5.

Färe R, Grosskopf S. Nonparametric productivity analysis with undesirable outputs: Comment. Am J Agr Econ 2003;85:1070-1074. https://www.jstor.org/stable/1244786.

Färe R, Grosskopf S. A comment on weak disposability in nonparametric production analysis. Am J Agr Econ 2009;91:535-538. https://www.jstor.org/stable/20492450.

Färe R, Grosskopf S, Lovell CAK, Yaisawarng, S., Derivation of shadow prices for undesirable outputs: a distance function approach. Rev Econ Stat 1993;75:374-380. https://www.jstor.org/stable/2109448.

Färe R, Grosskopf S, Pasurka CA. Tradable permits and unrealized gains from trade. Energy Econ 2013;40:416-424. https://doi.org/10.1016/j.eneco.2013.07.015.

Färe R, Grosskopf S, Pasurka CA. Potential gains from trading bad outputs: The case of U.S. electric power plants. Resour. Energy Econ 2014;36:99-112. https://doi.org/10.1016/j.reseneeco.2013.11.004.

Färe R, Grosskopf S, Weber WL. Shadow prices and pollution costs in U.S. agriculture. Ecol Econ 2006;56(1):89-103. https://doi.org/10.1016/j.ecolecon.2004.12.022.

Førsund FR. Good Modelling of Bad Outputs: Pollution and Multiple-Output Production. Int Rev Environ Resour Econ 2009;3(1):1-38. http://dx.doi.org/10.1561/101.00000021.

Førsund FR. Multi-equation modelling of desirable and undesirable outputs satisfying the materials balance. Empir Econ 2018;54:67-99. https://doi.org/10.1007/s00181-016-1219-9.

Harkness E. CO2 Shadow Prices in the U.S. Electric Utility Industry: Calculating the Costs of Reducing CO2 Emissions Senior Thesis Projects, 2003–2006 University of Tennessee, Knoxville; 2006. Available at: <http://trace.tennessee.edu/cgi/viewcontent.cgi?article=1066&context=utk_interstp3> [accessed July 2018].

Lauwers L, Van Huylenbroeck G, Rogiers G. Technical, economic and environmental efficiency analysis of pig fattening farms. In The 9th European congress of agricultural economists Warschau, Polen; 1999.

Lederer M. Market making via regulation: the role of the state in carbon markets. Regul Gov 2012;6(4):524-44. https://doi.org/10.1111/j.1748-5991.2012.01145.x.

Lee C–Y, Zhou P. Directional shadow price estimation of CO2, SO2 and NOx in the United States coal power industry 1990-2010. Energy Econ 2015;51:493-502. https://doi.org/10.1016/j.eneco.2015.08.010.

Lee SC, Oh DH, Lee JD. A new approach to measuring shadow price: reconciling engineering and economic perspectives. Energy Econ 2014;46:66-77. https://doi.org/10.1016/j.eneco.2014.07.019.

Leleu H. Shadow price of undesirable outputs in nonparametric analysis. Eur J Oper Res 2012;231:474-480. https://doi.org/10.1016/j.ejor.2013.05.028.

Li W, Jia ZJ. The impact of emission trading scheme and the ratio of free quota: a dynamic recursive CGE model in China. Appl Energy 2016;174:1-14. https://doi.org/10.1016/j.apenergy.2016.04.086.

Liu L, Sun X, Chen C, Zhao E. How will auctioning impact on the carbon emission abatement cost of electric power generation sector in China? Appl Energy 2016;168:594-609. https://doi.org/10.1016/j.apenergy.2016.01.055.

Lozano S, Villa G, Brännlund R. Centralised reallocation of emission permits using DEA. Eur J Oper Res 2009;193(3):752-760. https://doi.org/10.1016/j.ejor.2007.07.029.

Mahlberg B, Sahoo BK. Radial and non-radial decompositions of Luenberger productivity indicator with an illustrative application. Int J Prod Econ 2011;131:721-726. https://doi.org/10.1016/j.ijpe.2011.02.021.

Marklund PO, Samakovlis E. What is driving the EU burden-sharing agreement: efficiency or equity? J Environ Manage 2007;85(2):317-329. https://doi.org/10.1016/j.jenvman.2006.09.017.

Molinos-Senante M, Hanley N, Sala-Garrido R. Measuring the CO_2 shadow price for wastewater treatment: A directional distance function approach. Appl Energy 2015;144:241-249. https://doi.org/10.1016/j.apenergy.2015.02.034.

Molinos-Senante M, Maziotis A, Sala-Garrido R. Estimating the cost of improving service quality in water supply: a shadow price approach for England and Wales. Sci Total Environ 2016;539:470-477. https://doi.org/10.1016/j.scitotenv.2015.08.155.

Murty S, Russell RR, Levkoff SB. On modeling pollution-generating technologies. J Environ Econ Manage 2012;64(1):117-135. https://doi.org/10.1016/j.jeem.2012.02.005.

Newell Richard G, Stavins Robert N. Cost heterogeneity and the potential savings from market-based policies. J Regul Econ 2003;23 (1):43-59. https://doi.org/10.1023/A:1021879330491.

Peidong Z, Yanli Y, Yonghong Z. Opportunities and challenges for renewable energy policy in China. Renew Sustain Energy Rev 2009;13(2):439-49. https://doi.org/10.1016/j.rser.2007.11.005.

Shortall OK, Barnes AP. Greenhouse gas emissions and the technical efficiency of dairy farmers. Ecol Indic 2013;29,478–488. https://doi.org/10.1016/j.ecolind.2013.01.022.

Song M, Wang J. Environmental efficiency evaluation of thermal power generation in China based on a slack-based endogenous directional distance function model. Energy 2018;161:325-336. https://doi.org/10.1016/j.energy.2018.07.158.

Stavins Robert N. Transaction costs and tradable permits. J Environ Econ Manage 1995;29(2):133-148. https://doi.org/10.1006/jeem.1995.1036.

Sueyoshi T, Goto M. Should the US clean air act include CO2 emission control? Examination by data envelopment analysis. Energy Policy 2010;38:5902-5911. https://doi.org/10.1016/j.enpol.2010.05.044.

Sueyoshi T, Goto M. Returns to scale vs. damages to scale in data envelopment analysis: An impact of US clean air act on coal-fired power plants. Omega 2013;41:164-175. https://doi.org/10.1016/j.omega.2010.04.005.

Wang K, Wei Y-M., Huang ZM. Potential gains from carbon emissions trading in China: A DEA based estimation on abatement cost savings. Omega 2016;63:48-59. https://doi.org/10.1016/j.omega.2015.09.011.

Wang K, Wei Y-M, Zhang X. A comparative analysis of China's regional energy and emission performance: Which is the better way to deal with undesirable outputs? Energy Policy 2012;46:574-584. https://doi.org/10.1016/j.enpol.2012.04.038.

Wang K, Mi Z, Wei YM. Will pollution taxes improve joint ecological and economic efficiency of thermal power industry in China? A DEA-based materials balance approach. J Ind Ecol 2018; in press. https://doi.org/10.1111/jiec.12740.

Wang K, Wei YM, Huang Z. Environmental efficiency and abatement efficiency measurements of China's thermal power industry: A data envelopment analysis based materials balance approach. Eur J Oper Res 2018;269(1): 35-50. https://doi.org/10.1016/j.ejor.2017.04.053.

Wei C, Lochel A, Liu B. An empirical analysis of the CO2 shadow price in Chinese thermal power enterprises. Energy Econ 2013;40:22-31. https://doi.org/10.1016/j.eneco.2013.05.018.

Wei YM, Mi ZF, Huang Z. Climate policy modeling: an online SCI-E and SSCI based literature review.

Omega 2014;57:70–84. https://doi.org/10.1016/j.omega.2014.10.011.

Xian Y, Wang K, Shi X, Zhang C, Wei YM, Huang Z. Carbon emissions intensity reduction target for China's power industry: An efficiency and productivity perspective. J Clean Prod 2018;197:1022-1034. https://doi.org/10.1016/j.jclepro.2018.06.272.

Yang HL, Pollitt M. Incorporating both undesirable outputs and uncontrollable variables into DEA: The performance of Chinese coal-fired power plants. Eur J Oper Res 2009;197:1095–1105. https://doi.org/10.1016/j.ejor.2007.12.052.

Zhao X-G, Wu L, Li A. Research on the efficiency of carbon trading market in China. Renew Sustain Energy Rev 2017;79:1-8. https://doi.org/10.1016/j.rser.2017.05.034.

Zhou P, Zhang L, Zhou DQ, Xia WJ. Modeling economic performance of interprovincial CO_2 emission reduction quota trading in China. Appl Energy 2013;112:1518-1528. https://doi.org/10.1016/j.apenergy.2013.04.013.

Zhou P, Zhou X, Fan LW. On estimating shadow prices of undesirable outputs with efficiency models: a literature review. Appl Energy 2014;130:799-806. https://doi.org/10.1016/j.apenergy.2014.02.049.