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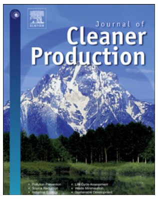

# Efficient allocation of $CO_2$ emissions in China: a zero sum gains data envelopment model

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ABSTRACT

The appropriate allocation of $CO_2$ emission quotas can build up a solid foundation for future emissions trading. Building $CO_2$ emissions allocation mechanism has significant practical implications. Based on radial zero sum gains data envelopment (ZSG-DEA) allocation model, this paper uses a non-radial ZSG-DEA model to allocate $CO_2$ emissions between different Chinese provinces. Unlike previous studies treating $CO_2$ as the input variable, we treat $CO_2$ as the undesirable output variable. The modified model can better reflect macro-production process while earlier relevant models treated $CO_2$ emissions as inputs. This paper contributes to the existing resource allocation method and allocates China's provincial $CO_2$ emissions from the view of technical efficiency. The results of our paper reveal that (1) between 2006 and 2010 the cumulative optimal amounts of $CO_2$ emissions were higher than the actual amounts in 12 provinces, and lower in other 18 provinces. (2) Several energy-abundant provinces such as Shanxi and Inter Mongolia need to take more responsibilities in $CO_2$ emissions reduction. (3) After the ZSG-DEA allocation, all provinces' $CO_2$ emissions are on ZSG-DEA frontier, which reflects the overall "Pareto Optimality".

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## 1. Introduction

Climate change has attracted global attentions, not only from developed countries, but also from developing countries. As the largest developing country, China has taken various measures for reducing its overall $CO_2$ emissions. The Chinese government set up a goal of reducing $CO_2$ emissions per unit gross domestic product (GDP) by 17% until 2015 in 2011, compared to the 2010 level (Geng, 2011). Achieving this target requires integrated efforts from all the provinces in China. However, due to different economic and social development levels, as well as other features across different provinces, the appropriate allocation of regional emission reduction targets need to follow the "common but differential" principle. Although the Chinese central government has set an emission reduction target for each province, such a target was mainly based upon the local GDP values, which means that more developed provinces should take more stringent reduction targets. This may result in that these provinces may feel reductant to take further efforts, while those less developed west provinces may not face too much emission reduction pressure. Consequently, more efforts should be made in order to assign more appropriate emission reduction targets to different provinces by considering local situations. Especially, with the newly established $CO_2$ emission trade markets in several pilot provinces, how to set up a reasonable $CO_2$ emission allocation mechanism is crucial so that the whole country can move toward low carbon development.

Academically, the allocation of $CO_2$ emissions has been widely studied. Holmberg et al. (2012) used the energy, exergy and market based methods to allocate $CO_2$ emissions and fuel costs. Wei et al. (2014) presented a systematic and quantitative method to achieve the "common but differentiated responsibility" $CO_2$ emission allocation principle. Pan et al. (2014a,b) emphasized "Equitable Access to Sustainable Development" for per capita cumulative $CO_2$ emission rights allocation schemes. Morini et al. (2013) raised a method for the optimal demand allocation

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among combined heat and power (CHP) and renewable energy systems to minimize the primary energy consumption. Hasan et al. (2014) presented a benefit-based allocation method by using a Shapley value approach. Wang et al. (2014) allocated $CO_2$ emission quotas to major countries using different regimes for a sample period of 2011–2100. Levihn (2014) compared different allocation methods and discusses both advantages and disadvantages of each method.

Different from these previous studies, this paper attempts to employ data envelopment analysis (DEA) to allocate $CO_2$ emissions based upon the environmental production technology proposed by Färe et al. (1989). The applicability of DEA in resource allocation has been investigated. For example, Cook and Kress (1999) discussed the allocation of constant input or output variables of the same conditions. Yan et al. (2002) measured the distribution of various resources. Beasley (2003) completed constant inputs distribution by using nonlinear planning. Lozano and Villa (2004, 2005) applied their allocation method in an electric power enterprise with two stages of the center distribution. Asmild et al. (2009) improved the central allocation model. Chang and Lai (2013) allocated carbon allowances for the transportation industry. Yu et al. (2014) allocated $CO_2$ emission reduction targets at the provincial level with fuzzy cluster and Shapley value decomposition. Wei et al. (2012) used a slacks-based DEA model to study the allocation of $CO_2$ abatement in various Chinese provinces. Wu et al. (2013) introduced a centralized DEA model for reallocation of emission permits. Feng et al. (2015) proposed a new two-step method with DEA-based centralized allocation model. Among these DEA models, the zero sums gains DEA model (i.e. ZSG-DEA) developed by Lins et al. (2003) and Gomes and Lins (2008) received increasing attentions. For instance, Hu and Fang (2010) used this model for market share allocation. Wang et al. (2013) used it for $CO_2$ emissions allowance in China.

Currently, the retrospective “grandfather” principle (e.g., EU and Republic of Korea) is usually applied for allocating region $CO_2$ emissions. This allocation mechanism considers historical $CO_2$ emissions amounts, but lacks practical meanings. Technical efficiency can reflect relative performance for a certain decision making unit (DMU) in the whole system and can better reflect more realistic facts. Therefore, the allocation mechanism based on the technical efficiency is a good supplementary method for other allocation mechanisms. Under such a circumstance, the main purpose of this paper is to study the efficient allocation of $CO_2$ emissions from a production efficiency point of view. It contributes to the knowledge development by constructing a ZSG-DEA model based on the environmental DEA technology for allocating $CO_2$ emissions across different provinces in China. Different from Gomes and Lins (2008) and Lin and Ning (2011), we follow environmental production technology analysis framework. We suggest $CO_2$ emissions are the undesirable output produced along with the desirable outputs (e.g. GDP). This treatment of $CO_2$ emissions conforms to the Chinese reality and improves the method that uses $CO_2$ emissions as the input variable. Particularly, in December 2014, the Chinese central government released a new regulation guiding the trade of carbon emission quotas. This paper can help facilitate the implementation of this regulation by allocating the appropriate regional $CO_2$ emissions. It proposes $CO_2$ emissions allocation from an efficiency perspective so that valuable policy implications can be provided to those decision-makers for preparing appropriate energy conservation and $CO_2$ emissions reduction policies. The rest of this paper is organized as below. After this introduction section, Section 2 presents research methodology, including model development and data collection/treatment. Section 3 presents research results and policy implications. Section 4 draws research conclusions.

## 2. Methodology

### 2.1. Model development

The ZSG-DEA model was first proposed by Lins et al. (2003) in order to estimate the winning efficiency of different countries in Olympics. The idea is that the total amount of an input (output) is fixed so that a decrease in the input (output) for one decision making unit (DMU) can lead to an increase in the input (output) for another DMU. It suggests that in ZSG-DEA the resource allocation is highly effective. After the reallocation of resources by using the ZSG-DEA model, the DMUs with lower technical efficiency scores can reach the frontier of best practice. In the ZSG-DEA model, two allocation principles, including average allocation and linear allocation, are often adopted. The liner allocation is more often used, such as the two ZSG-DEA application cases conducted by Gomes and Lins (2008) and Hu and Fang (2010). In the following part we present how to develop such a ZSG-DEA model.

Assuming that there are $G$ decision making units (DMUs) which convert $s$ inputs into $t$ outputs. Let $x_{ig}$ denote the $i$-th input and$y_{jg}$ denote the $j$-th output for $\text{DMU}_g$. The classic output-oriented CCR model which was proposed by Charnes et al. (1978) for calculating the technical efficiency of $\text{DMU}_g$ can be expressed in equation (1).

$$\begin{aligned}&\text{Max}\ \ h_g\\&\text{s.t.}\ \sum_{g=1}^{G}\lambda_g x_{ig}\le x_{ig},\quad i=1,\ldots,s\\&\sum_{g=1}^{G}\lambda_g y_{jg}\ge h_g y_{jg},\quad j=1,\ldots,t\\&\lambda_g\ge 0,\quad g=1,\ldots,G\end{aligned}\tag{1}$$

where, $x_{ig}$ represents the $i$-th input and $y_{jg}$ represents the $j$-th output for $\text{DMU}_g$. Once Equation (1) is solved, the ZSG-DEA model can be constructed by using the efficiency scores derived from Equation (1). As discussed by Gomes and Lins (2008), the output-oriented ZSG-DEA model can finally be formulated in Equation (2).

$$\begin{aligned}&\text{Max}\ \ h_{rg}\\&h_{rg}y_{ig}\le\sum_p\lambda_p y_{ip}\left|1-\frac{y_{ip}(h_p-1)}{\sum\limits_{p\ne k}y_{ip}}\right|\\&\sum_p\lambda_p x_{jp}\le x_{jg}\\&\lambda_p\ge 0\quad\text{for}\ \forall\ p\end{aligned}\tag{2}$$

where $h_p$ represents expansion factor for $\text{DMU}_p$ that can be calculated from Equation (1), and $h_{rg}$ represents expansion factor of $\text{DMU}_g$ evaluated by ZSG-DEA.

Fig. 1 illustrates the allocation principle of the ZSG-DEA model with a single input and output case. Comparing the output-oriented CCR model with the ZSG-DEA model, we can find that $\text{DMU}_A$ with a lower technical efficiency from the CCR model can improve its efficiency by increasing its output level. On the other hand, $\text{DMU}_B$ with a higher technical efficiency becomes less efficient through decreasing its output level. After the reallocation of output, all the DMUs reach the ZSG-DEA frontier with the same efficiency score of unity.

The ZSG-DEA model has been widely used for the cases with single input or output variables in resource allocation. Examples of such studies include Gomes and Lins (2008), Hu and Fang (2010), Fonseca et al. (2010), and Sun et al. (2012). With the increasing attention on reducing $CO_2$ emissions, several researchers, e.g. Gomes and Lins (2008) and Lin and Ning (2011), have also

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