Energy Policy 82 (2015) 62–80

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

A tripartite equilibrium for carbon emission allowance allocation in the power-supply industry

Jiuping Xu [a,b,*], Xin Yang [a,b], Zhimiao Tao [a,b]

[a] Low Carbon Technology and Economy Research Center, Sichuan University, Chengdu 610064, PR China
[b] Business school, Sichuan University, Chengdu 610064, PR China

HIGHLIGHTS

- A three-level decision model is proposed for allowance allocation policy-making.
- The relationship between the regional authority, power plants and grid company is considered.
- GA is combined with KKT conditions to search for the tripartite equilibrium.
- Appropriate emission limits have a great effect on achieving the reduction target.
- Power plants with lower carbon intensity should be allocated more allowances.

ARTICLE INFO

Article history:
Received 6 November 2014
Received in revised form
9 January 2015
Accepted 25 February 2015

Keywords:
Carbon emission allowance allocation
Power-supply industry
Tripartite equilibrium
Emission limits

ABSTRACT

In the past decades, there has been a worldwide multilateral efforts to reduce carbon emissions. In particular, the "cap-and-trade" mechanism has been regarded as an effective way to control emissions. This is a market-based approach focused on the efficient allocation of initial emissions allowances. Based on the "grandfather" allocation method, this paper develops an alternative method derived from Boltzmann distribution to calculate the allowances. Further, with fully considering the relationship between the regional authority, power plants and grid company, a three-level multi-objective model for carbon emission allowance allocations in the power-supply industry is presented. To achieve tripartite equilibrium, the impacts on electricity output, carbon emissions and carbon intensity of the allocation method, allocation cap, and emission limits are assessed. The results showed that the greatest impact was seen in the emission limits rather than the allocation cap or allocation method. It also indicated that to effectively achieve reduction targets, it is necessary to allocate greater allowances to lower carbon intensity power plants. These results demonstrated the practicality and efficiency of the proposed model in seeking optimal allocation policies.

1. Introduction

The Fifth Assessment of the Intergovernmental Panel on Climate Change (IPCC) has shown that the climate is changing (IPCC, 2013). For example, global mean surface air temperatures over land and oceans have increased over the last 100 years, and the extreme weather and climate events have an increasing trend (WMO-No.1119; Xu et al., 2014a). Rapid carbon emissions growth (short for GHG emissions) is regarded as one of the largest contributors to these changes, having risen by 30% between 2000 and 2010 (Peters, 2013; IEA, 2012). In particular, fossil fuel burning for electricity purposes has been one of the major contributors to human activity carbon increases over the last 20 years.

Because of the harmful impact brought by excessive carbon emissions, several policy instruments have been developed to attempt to mitigate climate change and reduce carbon emissions, such as carbon taxes, command-and-control, and cap-and-trade (Keohane, 2009; Cong and Wei, 2010b; Hahn, 2009). The cap-and-trade mechanism, also known as the emission trading scheme (ETS), is an application of Coase (1960) Theorem, and has proved to be effective in controlling emissions and has been successfully put into practice (Clo, 2009). In this mechanism, the initial carbon emission allowances are defined and allocated for free or at auction or a combination of both (Cong and Wei, 2012; Zhang and Li, 2011). Free allocations presently dominate and are expected to continue to play an important role to 2020 (Hong et al.,

* Corresponding author at: Low Carbon Technology and Economy Research Center, Sichuan University, Chengdu 610064, PR China. Fax: +86 28 85415143.
E-mail address: xujiuping@scu.edu.cn (J. Xu).

http://dx.doi.org/10.1016/j.enpol.2015.02.029
0301-4215/

2014). Research on free carbon emission allowance allocations has attracted significant attention in the last few decades, with many scholars having conducted in-depth studies on international carbon emission allowance allocations. Grubler and Nakicenovic (1994) proposed that all countries should be assigned a consistent emissions reduction rate, which ignored the inherent relationship between emissions and population or human activities. The per capita emission-based allocation, signifying that everyone possesses equal emission rights, was suggested by Grubb (1990). This concept has received considerable attention but opposed by several high per capita emission countries. The per unit GDP-based allocation, in which all countries are assumed to have equal emissions per GDP, is another efficient method (Phylipsen et al., 1998). At the same time, some attention has been paid to allocating emission allowances within a specific country. For instance, Yi et al. (2011) introduced a carbon emission intensity-based allocation method, which was applied to the allocation of reduction targets for provinces in China. An improved zero sum gains data envelopment analysis optimization model was proposed by Wang et al. (2013) to realize China's national mitigation targets through a regional allocation of emission allowances. Yu et al. (2014) put forward an approach based on the PSO algorithm, fuzzy c-means clustering algorithm, and Shapley decomposition to determine carbon emission reduction target allocation. Besides these approaches, other allocation approaches have been proposed at the sector level, such as “grandfathering”, allowances based on historical emissions and "benchmarking", allowances based on energy input or product output (Hong et al., 2014). Chang and Lai (2013) proposed carbon emission reduction models for the transportation industry using carbon allowance allocation policies.

In addition, a series of more comprehensive and complex allocation models have been developed. Phylipsen et al. (1998) presented a Triptych sector approach which included per capita emissions, per capita GDP, and carbon emissions per unit GDP. Park et al. (2012) introduced the Boltzmann distribution in the physical sciences to allocate emission allowances. These studies have contributed to the improvement of viable solutions to the carbon emission allowance allocation problem (CEAAP) significantly, but these existing allocations are only based on the entity's historical behaviors and have not often considered its possible reactions for the allowances. In fact, under the “cap-and-trade” mechanism, each entity's actual emissions may not be equal to the allowances it receives. The achievement of controlling and reducing emissions depends on the user performance. Therefore, it is necessary to include user opinions in the allocation process. This paper analyzes the CEAAP in the power-supply industry, particularly.

As large carbon emitters, power plants must be considered when seeking to mitigate carbon emissions (Chappin, 2006; Cong and Wei, 2010a; Chen et al., 2010, 2013; Zhu et al., 2013). They are in charge of electricity generation, which is influenced by the regional authority's allocation policy. At the same time, when they estimate and seek to maximize profits, it is often difficult to estimate electricity sale revenues because these are decided by the grid company under the “bidding on power net” mechanism. In turn, power plants can also have an impact on the decision-making of regional authority and grid company through carbon emissions and their sale pricing decisions, respectively. Therefore, the allocation involves the regional authority, power plants, grid company and depends on the interactive relationship. With this in mind, the CEAAP in the power-supply industry is presented as a three-level problem with three decision-makers: the regional authority, power plants and grid company. In addition, since there are many uncertainties in the allocation system (Cong and Wei, 2010a; Zhu et al., 2013), fuzzy random theory is used to describe the practical problems (Kwakernaak 1978a,b; Xu and Tao, 2012; Xu et al., 2014b). To deal with the multi-level model, KKT optimization conditions (Sinha and Sinha, 2002) are used to transform this tripartite arrangement to a game between the regional authority and power plants. And a KKT-based interactive genetic algorithm (Hejazia et al., 2002) is followed to search for the points of equilibrium. Finally, practical examples are discussed to seek an efficient allocation policy for emissions control. These results indicated that an appropriate emissions limit and allocating more allowances to power plants with lower carbon intensity are advisable. It is proved that our optimization method was very practical and efficient in solving the CEAAP in the power-supply industry.

The remainder of this paper is organized as follows. Section 2 is the methodology part, including description of the key problem statement for CEAAP in the power-supply industry, the formulation of a three-level mathematical model and the search of an efficient solution approach. In Section 3, an application in Shenzhen ETS is presented to explore useful results. To confirm the generality of these results, a general case and some further discussions are shown in Section 4. Finally, Section 5 gives our conclusions and policy implications.

2. Methods

2.1. Key problem statement

The power-supply industry CEAAP is a complex system (Fig. 1) comprising a carbon trading market, an electricity generation market, a fuel supply market, consumers, the government, regional authority, power plants and grid company (Ottino, 2004; Zhu et al., 2013). Therefore, efficient allocation policies are required, as unsuitable allocations may not only fail to achieve emissions control targets, but also result in local electricity supply shortages or even system collapse (Wang et al., 2013; Yu et al., 2014).

In the allocation system, as the regional authority is directly responsible for the allowances allocation, it has a close relationship with the power plants. The regional authority seeks to control and reduce carbon emissions with limited allowances, but the power plants desire greater allowances and emissions levels for the sake of themselves. Besides, the ETS often means that each plant's emissions could not be equal to its allowances, the regional authority's emissions mitigation target is heavily dependent on the performance of the power plants.

There also exists an interesting and close relationship between the power plants and the grid company. Power plant electricity generation costs and sales prices increase when carbon emissions are controlled and treated as assets (Cong and Wei, 2010). Consequently, the grid company decides on each power plants electricity sales with the primary goal of minimizing purchase costs under the “bidding on the power net” mechanism. Therefore, power plant generation plans are influenced by decisions beyond their control.

In summary, the power-supply industry CEAAP is a tripartite game between the regional authority, power plants and grid company. In an attempt to find an equilibrium, this paper uses a multi-level analysis to develop a hierarchical structure which simulates this tripartite interaction (Fig. 2). The regional authority is appeared in the “Authorities level” to make allocation policies, including decisions on allowances allocation and emissions limitation. It attempts to maximize the minimal allocation satisfaction and the overall carbon efficiency, while meeting each plant's allowances demand. After obtaining the allowances, the power plant focuses on economic profits maximization with optimal output decision, which must satisfy the capacity and emissions