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# Carbon emissions reductions oriented dynamic equilibrium strategy using biomass-coal co-firing

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ABSTRACT

Carbon emissions are posing continuing threats to climate change and becoming the important evaluation indicator for sustainable development. The amount of global carbon emission is increasing largely, with coal-fired power plants (CPP) being the major contributor. This study proposes dynamic equilibrium strategy based on biomass-coal co-firing method to reduce carbon emissions, in which bi-level programming method is employed to build a cooperative relationship between the authority and CPPs, dynamic programming method is used to handle biomass availability time conflict, multi-objective programming method is applied to seek the trade-off between economic development and environmental protection, and furthermore uncertainty theory is introduced to address imprecise uncertain parameters. The proposed model is then applied to a case in Jiangsu, China, to demonstrate its efficiency and practicality, and an interactive algorithm is developed as the solution approach to represent the objectives and limitations between several stakeholders. Based on analyses and discussions under different scenarios, the proposed method can achieve economic-environmental coordination and realize sustainable development, and moreover a carbon emissions allocation competition mechanism is recommended. This methodology could be used in various countries and industries with only slight adjustments needed to some parameters.

## 1. Introduction

Global energy consumption has significantly increased in recent decades due to rapid urbanization, industrial development, world economic growth and rising populations (Mallick et al., 2017). The BP statistical review of world energy stated that in 2017, coal still accounted for 28.1% of global primary energy consumption and was ranked second after oil as an energy source. However, reliance on coal has resulted in excessive greenhouse gas emissions such as carbon emissions that have significantly contributed to global climate change (Pain, 2017; Basu, 1999; Li et al., 2009). According to BP Energy Outlook 2018, global carbon emissions have been growing relentlessly for nearly 50 years, although the growth has gradually slowed in recent year (Global, 2018). Global carbon emissions have risen from 16 Gt in 1970 to 36 Gt in 2015, an increase of 125% (Olivier et al., 2015). The concentration of carbon emissions in the atmosphere is the largest global environmental risk (Programme, 2017). Two thirds of the world's electricity is generated by fossil fuel power plants, of which coal-fired power plant (CPP) is one of largest sources of carbon emissions (Global, 2015; Service, 2017). Under these circumstances, carbon emissions from CPPs need to be urgently reduced.

Relevant studies on reducing carbon emissions from CPPs have focused on either hard-technology or soft-technology (Lv et al., 2016). Hard-technology, which concentrates on technological innovation or investment to reduce carbon emissions, is regarded as the most effective solution. Mao et al. (2014) claimed that coal washing, retrofitting the stream turbine flow passage, and carbon capture and storage/sequestration were all viable technical reduction measures, and Low et al. (2017) suggested utilizing $TiO_2$ to increase carbon dioxide adsorption. Although hard-technology has had a significant positive effect on carbon emissions reductions, it is generally expensive and beyond the ability of most developing countries (Xu et al., 2017). Therefore, soft-technology has been the more favored option (Goto et al., 2013; Xu et al., 2015; Li, 2012). Soft-technology seeks to modify the production operations or management methods without technological change and generally involves optimization methods or policy developments such

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as co-firing, carbon tax, and Cap-and-Trade (C&T) (Chen et al., 2015; Dai et al., 2014; Yearwood-Lee, 2015; Broek et al., 1996). Lin and Li (2011) claimed that although carbon tax was an immediate carbon price signal, it also had some disadvantages as the mitigation impacts were uncertain and rational carbon tax rates were hard to determine. Keohane (2009) and Grubb (2012) believed that C&T had some advantages over carbon tax as it was political feasibility, cost effectiveness and was able to control the cumulative quantity of carbon emissions; however, its procedures are complex and cost is relatively high. In this situation, biomass-coal co-firing method provides the simplest, most practicable and most cost-effective method for carbon emissions reductions (Baxter, 2005; Li et al., 2012; Liu et al., 2016; Tilman et al., 2009).

Biomass-coal co-firing has been extensively researched. This method has been proved to be a reasonable option for power generation and has been found to significantly reduce the environmental footprint of CPPs as it reduces not only net greenhouse gases but also $SO_2$ and $NO_x$ emissions because of biomass' lower carbon, sulfur, and fuel-bound nitrogen (Agbor et al., 2014; Hubweber et al., 2001; Weldu, 2017; Narayanan and Natarajan, 2007; Beagle and Belmont, 2016). Eksioglu and Karimi (2014) developed a non-linear optimization model from the perspective of CPPs that considered the additional costs and savings, loss of process efficiencies. And Yilmaz and Selim (2015) developed a fuzzy multi-objective strategy based decision making model to design the most profitable biomass supply chain. Several co-firing technologies have reached maturity; for example, Al-Mansour and Zuwala (2010) outlined three mature technological approaches: direct co-firing, in which biomass and coal were burned in the same or separate mills and burners; indirect co-firing, in which biomass a gasifier was installed to convert biomass into the coal furnace; parallel co-firing, in which separate biomass boiler and coal boiler were utilized. Basu et al. (2011) compared capital and operating costs of co-firing technologies in five CPPs, and concluded that direct co-firing method at lower ratios was the simplest and the lowest cost option. However, the greatest challenges associated with biomass-coal direct co-firing were co-firing ratio and biomass storage (Agbor et al., 2014; Rentizelas et al., 2009; Allen et al., 1998). Sahu et al. (2014) and Moon et al. (2013) found that a 10% biomass co-firing ratio was the peak acceptable mixing ratio for direct co-firing that had no irresolvable issues. To deal with biomass storage seasonal availability, Rentizelas et al. (2009) proposed combining multiple biomass supply chains to achieve the lowest cost storage. Although these studies have made some progress in addressing carbon emissions, they have tended to focus only on a single decision maker, only on economic development or only on biomass storage from a short-term perspective. The realistic situation is more complicated and further improvements are still necessary.

In this paper, a dynamic equilibrium strategy based bi-level multi-objective multistage biomass-coal co-firing method is proposed to reduce carbon emissions. In reality, there are several decision makers involved in carbon emissions reductions: the authority and the CPPs. The authority first makes an initial decision based on optimizing itself and predicting CPPs' decisions, after which the CPPs make decisions to satisfy the authority's decisions and profits maximization objective. As the CPPs' decisions could influence the authority's objectives, these are fed back to the authority. Then the authority adjusts its initial decision, following which the CPPs again make decisions and provide feedback. This process is repeated until a final scheme acceptable to the authority and all the CPPs is determined (Lv et al., 2016; Zhang et al., 2015). In the process, as the authority is the leader and CPPs are the followers, the relationship is similar to Stackelberg game. Therefore, bi-level programming method is adopted to seek a Stackelberg-Nash equilibrium (Colson et al., 2007; Sinha et al., 2014). As for the authority, it attaches great importance to both economic development and environmental protection, and has an overall sustainable development objective. Therefore, multi-objective programming method is used to seek the trade-off between the economy and the environment. In this paper, carbon emissions minimization represents environmental protection objective due to their important role in global climate change, and revenue maximization represents economic development objective as it can guarantee economic and society stability and development. In regard to CPPs, secure and long-term biomass storage is critical. As seasonal availability occurs to biomass storage, dynamic programming method is applied to determine the optimal decisions in each stage to ensure that CPPs are able to maximize profits over a long-term perspective. Uncertainty theory is also adopted to estimate the exact value of the uncertain parameters such as emissions factors, which are uncertain because of the unstable combustion process (Xu and Zhou, 2011; Liu et al., 2015).

Based on the above discussion, to reduce carbon emissions, this paper proposes a comprehensive methodology that integrates bi-level programming method, multi-objective programming method and dynamic programming method to achieve a cooperative relationship between the authority and the CPPs, balance the trade-off between environmental protection and economic development, and settle biomass storage time conflicts under an uncertain environment. Mathematical modeling method is employed to express this dynamic equilibrium strategy based bi-level multi-objective multistage biomass-coal co-firing method in the following section.

## 2. Modeling

### *2.1. Assumptions*

(1) Co-firing at low ratios does not pose any threat or major problems to the boiler operations (Basu et al., 2011).
(2) Volatile matter of fuels can be completely burnt in the burners (Sami et al., 2001).
(3) Value-added tax rate the CPPs pay is fixed.
(4) This method is a single production period, with the production period divided into 12 months; at the beginning of the each production period, the fuel storage is reset.

### *2.2. Model for the local authority*

#### *2.2.1. Objective 1: maximizing revenue*

As it is difficult to deal with realistic uncertain decision making problems, uncertainty theory is used to assess the uncertain parameters. Uncertain parameters can be estimated to be within a certain range, in which the values of parameters are more likely to be. For instance, $\tilde{C}_{ji}$ is a trapezoidal fuzzy number, the certain range of which is from the minimum value $r_{11}$ to the maximum value $r_{14}$, and the most likely value of which is between $r_{12}$ and $r_{13}$. This trapezoidal fuzzy number can be written as $\tilde{C}_{ji} = (r_{11}, r_{12}, r_{13}, r_{14})$, where $r_{11} \le r_{12} \le r_{13} \le r_{14}$. To value the exact value of trapezoidal fuzzy numbers, the expected value operator method proposed by Xu and Zhou (2011) is adopted as Fig. 1.

$$\tilde{C}_{ji} \to E\left[\tilde{C}_{ji}\right] = \frac{1-\theta}{2}\left(r_{11} + r_{12}\right) + \frac{\theta}{2}\left(r_{13} + r_{14}\right) \tag{1}$$

To guarantee the stability and development of the economy and the society, the authority imposes value-added tax and fees on the carbon emissions quotas. Let $M$ be value-added tax rate, and $\sum_{s=1}^{S}\sum_{i=1}^{I} QE[\tilde{C}_{ji}]x_{jis}$ represents the annual profits of CPP $j$; therefore,