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An interval-fuzzy two-stage stochastic programming model for planning carbon dioxide trading under uncertainty

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ABSTRACT

In this study, an IFTSP (interval-fuzzy two-stage stochastic programming) method is developed for planning carbon dioxide (CO_2) emission trading under uncertainty. The developed IFTSP incorporates techniques of interval fuzzy linear programming and two-stage stochastic programming within a general optimization framework, which can effectively tackle uncertainties described in terms of probability density functions, fuzzy membership functions and discrete intervals. The IFTSP cannot only tackle uncertainties expressed as probabilistic distributions and discrete intervals, but also provide an effective linkage between the pre-regulated CO_2 mitigation policies and the associated economic implications. The developed model is applied to a case study of CO_2-emission trading planning of industry systems under uncertainty, where three trading schemes are considered based on different trading participants. The results indicate that reasonable solutions have been generated. They are help for supporting: (a) formulation of desired GHG (greenhouse gas) mitigation policies under various economic and system-reliability constraints, (b) selection of the desired CO_2-emission trading pattern, and (c) in-depth analysis of tradeoffs among system benefit, satisfaction degree, and CO_2 mitigation under multiple uncertainties.

1. Introduction

After decades of debate, there is now a clear scientific consensus that global warming is occurring and GHG (greenhouse gas) [e.g., carbon dioxide (CO_2)] arising from human activities is a major contributory factor [1]. Due to the combustion of fossil fuels principally, global atmospheric concentrations of CO_2 have risen about 36 percent since the Industrial Revolution, which accelerated the rate of global warming [2]. Global warming is one of the most significant environmental challenges that the world has ever faced, which may lead to the increase in surface temperature, the change in the global climate, the rise in ocean level, even the disruption in food production [3,4]. In order to mitigate and control the global warming, it is imperative to decrease CO_2-emission well below the current level. The major fuel consuming sectors contributing to CO_2-emission from fossil fuel combustion are power industry (e.g., oil, gas and coal power utilities) and energy-intensive industry (e.g., steel, cement and lime), which account for 41 and 28 percent of global man-made CO_2-emission, respectively [1,2]. It is questioned that whether energy supply that depends on fossil fuels for 85% of its energy need can meet GHG-mitigation requirement under a speedily expanding economy situation. A number of researchers are in a puzzle about how to balance the increasing demands of energy due to the economic development and the population growth, less fossil fuel consumption, and mandated requirement for GHG-emission reduction [5,6].

A large amount of research efforts were conducted for the implementation of GHG mitigation. For example, CO_2 capture and storage were used as potential carbon reduction options which could allow a smoother and less costly transition to a sustainable, low-carbon energy future, and plenty of sequestration facilities were built up for GHG capture [7–9]. Techniques of energy exploration and production were improved ceaselessly to offset the progressive depletion of world reserves: high carbon fuels (e.g., coal and crude oil) were replaced by lower carbon content hydrogenated fuels (e.g., biodiesel fuel), and non-CO_2 emitting energy sources were extensively used, such as low energy hydropower, nuclear, wind, geothermal and solar photovoltaic [10,11]. Besides, a number of other measures still could be taken, such as education and awareness raising, improvements in energy efficiency and measures to encourage the deployment of low-carbon technologies. Whereas a key policy requirement is carbon pricing, assigning

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a cost to emissions of greenhouse gases, through taxation, regulation, and/or emissions trading [12].

Thanks to the Kyoto Protocol, three flexible mechanisms (i.e., international emissions trading, clean development mechanism, and joint implementation) were proposed, which made great contribution to realize CO_2 reduction commitment in a cost-effective way. Among them, there is a growing international consensus that CO_2-emission trading is the most cost-effective way to meet the CO_2-emission limits [13,14]. Recently, when several countries developed domestic emission trading schemes, public and private sectors could initiate emission trading activities [15]. Kuik [16] assessed three alternative emission trading schemes at the domestic level: absolute cap-and-trade, relative cap-and-trade, and mixed schemes (that combined the elements of the above alternatives). Ellerman et al. [17] compared European Union fifteen countries' total costs of reaching the commitments of the Kyoto Protocol under trading and non-trading schemes, and the results proved trading scheme is a more cost-effective way to realize CO_2 reduction. Sijm [18] utilized marginal abatement cost curves generated from energy system models to analyze international emissions trading, and concluded that widening the market to include developing countries is more effective than the Annex B market solution. Rehdanz [19] developed a two-country game model to analyze the coordination of domestic markets for tradable emission permits, where countries determined their own emission reduction targets. Although these studies were effective for planning the tradable GHG-emission permits, most of them conducted deterministic analyses at a macroscopic level. In the real-world CO_2-emission abatement problems, uncertainties exist in a variety of energy-related processes and activities, such as exploitations of industrial raw material, processes of industrial production, demands/supplies of industrial products, inventories for CO_2 emission, and errors in the economic parameters [20]. Besides, uncertainties could also arise due to regulators' inconstant commitments to climate policies or changes of emission trading regulatory. Specifically, CO_2 discharged from various industrial activities can be influenced by stochastic events such as industrial product demand, which may fluctuate time to time. Meanwhile, the accuracy of information on generated industry production and cost/benefit coefficients are not sufficient, which may vacillate within a certain interval [6].

As a result, a number of research efforts were conducted to tackle these uncertainties. For example, Carlson et al. [21] examined the impact of uncertainty on actual CO_2-emission levels under trading schemes so as to limit the price volatility and concluded that staggered issuing of permits may enhance the effectiveness of a reconciliation period in reducing volatility. Kanudia et al. [22] introduced a multistage stochastic programming method into the MARKAL model to formulate a long-term energy development plan and to reduce CO_2-emission in Québec, Canada. Ling [3] proposed an interval stochastic two-stage linear programming model for managing CO_2-emission quota in power industry. Lin [23] developed an interval parameter two-stage stochastic model for supporting decisions of energy system planning and GHG-emission management at a municipal level. Although these studies involved in reflection of uncertainties in CO_2-emission management, little attention has been paid to CO_2-trading mechanism coupled with emission reduction measures. Chen et al. [6] developed a TISP (two-stage inexact-stochastic programming) model for planning GHG-emission trading within the electrical-power systems. The TISP could deal with uncertainties presented as probabilities and intervals; however, it had difficulties in reflecting uncertainty existing as fuzzy sets. In fact, results produced by optimization techniques can be rendered highly questionable in real-world problems, if the modeling inputs could not be expressed with precision. When the available information is poor as a whole, multiple uncertainties can be presented as random variables, intervals and/or fuzzy sets [24,25]. FP (Fuzzy programming) can handle uncertainties expressed as fuzzy sets, and it is effective in reflecting ambiguity and vagueness in resource availabilities [26,27].

Therefore, to better account for uncertainties presented in different formats in CO_2-emission trading planning, one potential approach is to introduce the FP technique into the TISP framework. This leads to an IFTSP (interval-fuzzy two-stage stochastic programming) method. The objective of this study is to develop such an IFTSP method for CO_2-emission trading planning within an integrated energy and carbon reduction system. The proposed method can deal with multiple forms of uncertainties, such as fuzzy, probabilistic distributions and interval values. Furthermore, it can support the analysis of various policy scenarios which are associated with different levels of economic penalties when the promised targets are violated. Then, a case study of planning regional industry will be provided for illustrating the applicability of the developed method, where three power plants, one steel factory, one cement factory, and one lime factory are involved. Three schemes for managing CO_2-emission, including "non-trading for all industrial units", "trading within three power plants and within three factories", and "trading among all industrial units", will be analyzed to achieve an optimal CO_2-emission management policy. The results will help decision makers gain deep insights into the tradeoffs between economic objective and CO_2-emission trading scheme.

2. Modeling formulation

Consider an industry system wherein a manager is responsible for allocating CO_2-emission permit to each CO_2 emitter within a multi-period horizon. The facilities for CO_2 mitigation include CS (capture and storage) and CA (chemical absorption). On the basis of the local management policy, a targeted CO_2-emission quota is allocated to each CO_2 emitter. If this quota is not exceeded, the industry system will bring normal benefits, and it is allowed to sell the difference between the actual emission level and its quota. On the contrary, if it is exceeded, CO_2 emitter has to use facilities to dispose the surplus CO_2-emission amounts or buy CO_2-emission permits from other industrial units that have excessive quota, resulting in an increased cost to this emitter. Under such a situation, the manager needs to optimize CO_2-emission amount of each emitter to achieve a maximized system benefit while satisfying the total CO_2-emission requirement. Moreover, uncertainties expressed as multiple formats such as interval values, probability density functions, and fuzzy sets existing in the study system should be reflected. Thus, the manager can formulate the problem as maximizing the entire system benefit while satisfying the goal of carbon reduction and complex uncertainty reflection.

2.1. Interval fuzzy linear programming

First, consider an IFLP (interval fuzzy linear programming) problem as follows [28]:

$$\text{Max}\, f^{\pm} \underset{\sim}{=} C^{\pm}X^{\pm} \tag{1a}$$

subject to

$$A^{\pm}X^{\pm} \underset{\sim}{\leq} B^{\pm} \tag{1b}$$

$$X^{\pm} \geq 0 \tag{1c}$$

where $A^{\pm} \in \{R^{\pm}\}^{m\times n}$, $B^{\pm} \in \{R^{\pm}\}^{m\times l}$, $C^{\pm} \in \{R^{\pm}\}^{l\times n}$ and $X^{\pm} \in \{R^{\pm}\}^{n\times l}$, $\{R^{\pm}\}$ denote a set of interval numbers; the '−' and '+' superscripts denote the lower and upper bounds of parameters/variables, respectively; and symbols $\underset{\sim}{=}$ and $\underset{\sim}{\leq}$ represent fuzzy equality and