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An integrated optimization modeling approach for planning emission trading and clean-energy development under uncertainty

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ABSTRACT

The growing concern for global warming caused by the increased atmospheric concentration of carbon dioxide (CO_2) has a significant effect on environmental and energy policies and economic activities, due to the ever-increasing use of fossil fuels such as coal, oil and natural gas throughout the world. A variety of complexities and uncertainties exist in CO_2-emission-related processes and various impact factors, such as CO_2-emission inventory, mitigation measure, and cost parameter. Decision makers face problems of how many clean-energy resources (or carbon credits) are needed to be replaced (or bought) by measuring electric-power benefits and uncertain economic penalties from random excess CO_2 exceeding to given discharge permits. In this study, an integrated optimization modeling approach is developed for planning CO_2 abatement through emission trading scheme (ETS) and clean development mechanism (CDM), where uncertainties presented in terms of fuzzy sets, interval values, and random variables can be addressed. The developed model is also applied to a case study of planning CO_2-emission mitigation for an electric-power system (EPS) that involves three fossil-fueled power plants (i.e., gas, oil and coal-power plants). Different trading schemes and clean-energy development plans corresponding to different CO_2-emission management policies have been analyzed. The results demonstrate that CO_2-emission reduction program can be performed cost-effective through emission trading and clean-energy development projects. Violation analyses are also conducted to demonstrate that different violation levels for model's objective and constraints have different effects on system benefit and satisfaction degree as well as emission trading and clean-energy development.

1. Introduction

The observed increase in globally averaged temperatures since the mid-20th century is very likely to have occurred due to the increase in anthropogenic greenhouse gas concentrations that leads to the warming of the Earth's surface and lower atmosphere [1]. Global warming is currently one of the most significant environmental challenges that the world has ever faced, which has led to increase in surface temperature, change in global climate, rise in ocean level, as well as disruption in food production [2,3]. Potential for climate change resulting from heightened levels of atmospheric carbon dioxide (CO_2) has long been recognized as a possible consequence of increasing utilization of fossil fuels as primary energy sources. CO_2 concentration has also increased from about 280 ppm in pre-industrial times to the current 350 ppm, with an estimated annual growth rate at around 1.8 ppm [4]. CO_2 concentrations in the atmosphere are expected to continue to rise due to the ever-increasing use of fossil fuels such as coal, oil and natural gas throughout the world. The growing concern for global warming caused by the increased atmospheric concentration of CO_2 has a significant effect on environmental and energy policies and economic activities [5,6].

Many effective measures to reduce CO_2-emissions are to replace fossil fuels by renewable energy sources (e.g., clean development mechanism, CDM), improve energy-convention efficiencies, utilize CO_2 capture/storage technologies, adopt economic incentives (e.g., carbon tax), and trade emission among public/private sectors [7–10]. Among them, there is a growing international consensus that emission trading is the most cost-effective way to realize CO_2 reduction commitment [11]. Emission trading, which is market-based strategy and can provide cost-effective and flexible

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environmental compliance for energy systems, has been regarded as one of the most promising policy alternatives for CO_2 reduction. In 2005, the European Union (EU) implemented an emission trading scheme (ETS) for certain industries and installations to partially fulfill its obligations under the Kyoto framework to reduce greenhouse gas (GHG) emissions; the major objective is to encourage the industry's biggest emitters to reduce their carbon emissions and invest in clean technologies. The European ETS and the CDM are the two largest carbon-trading schemes currently in operation throughout the world. CDM is established to support developing countries in achieving a sustainable development path, while at the same time assisting industrialized countries in achieving the Kyoto Protocol commitments [12]. CDM typically results in a transfer of GHG abatement technologies to developing countries in exchange for the GHG emission reduction credits [13]. The developed countries can offer money and technology to help developing countries establish low-carbon energy demonstration projects (e.g., wind energy demonstration project) to generate emission certificates.

Previously, many research works estimated the efficiencies of emission trading and clean-energy development efforts for reducing GHG emissions with a cost-effective way [14,15]. For example, Kuik and Mulder [16] assessed several emission trading schemes at the domestic level such as absolute cap-and-trade, relative-cap-and-trade, and mixed absolute- and relative-cap-and-trade. Rehdanz [17] 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. Szabetó al. [18] presented a global simulation model to quantitatively analyze the impacts of three carbon emission trading schemes on the cement sector. Ellerman et al. [19] 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. Buckman and Diesendorf [20] evaluated the medium-term effectiveness of emissions trading in stimulating renewable energy in Australia as well as the potential stimulatory contribution of the expanded renewable energy target with reference to Australia's availability of renewable energy resources and the unique design features of the mechanism. Although these studies were effective for planning the tradable GHG emission permits, most of them conducted deterministic analyses at a macroscopic level. In comparison, public and private sectors could initiate emission trading activities when domestic emission trading schemes were proposed in several countries [20]. In many literatures, the CDM was always analyzed within the global carbon market and rarely as an instrument for climate policies in industrialized countries, which has not received noticeable attention by decision makers for community or region level planning [21]. In fact, small-scale communities based CDM projects, which expanded access to energy services through the use of local renewable energy resources, and possessed the potential to contribute to local and national development objectives [22].

Uncertainty plays an important role in emission trading programs. There are many sources of uncertainty in modeling trading programs due to parameter estimation, input data, and model structure; uncertainties could arise due to regulators' inconstant commitments to climate policies or changes of emission trading regulatory. For example, emission inventories are often associated with inherent uncertainties due to the (i) use of simplified representations of averaged values, particularly for emission factors; and (ii) inaccuracy in basic socio-economic activity data, growth rate projections, equipment age, as well as methods, models and assumptions concerning emission processes [23,24]. Moreover, these uncertainties may vary widely depending on the type of GHG source, value of global warming potential used, change in methodologies for GHG emission estimation, the relative share of pollutants estimated with a specific emission factor, country-specific reporting procedures, and socio-economic activity data [25].

For decades, a number of research efforts have been conducted on carbon emission trading in response to such complexities and uncertainties [4,9,23,26,27]. In fact, uncertainty may have essentially two origins: randomness due to natural variability of the observed phenomenon resulting from heterogeneity or stochasticity and imprecision due to lack of information resulting from systematic measurement error or expert opinion [28]. For example, GHG emissions from the electricity generation sector can be influenced by stochastic events such as electricity demand, which may fluctuate from time to time [29]. Energy demands can be classified into multiple end-users (e.g. residential, commercial, industrial, transportation, and agricultural users). The demand from each sector can then be represented by the fixed input of fuel and electricity. Many impact factors and their interactions such as population growth rate, economic development, end-user habit, and supply/service policy could lead to uncertain energy demand levels. Besides, for CO_2 reduction through emission trading and clean-energy development, penalties are usually necessary to enforce decision makers reducing CO_2 discharge from electric-power plants. Decision makers then face problems of how many clean-energy resources (or carbon credits) are needed to be replaced (or bought) by measuring electric-power benefits and uncertain economic penalties from random excess CO_2 exceeding to given discharge permits. Therefore, how to estimate the efficiency of trading efforts by considering such random variables becomes a critical issue for the decisions to be conducted.

One possible approach for better tackling uncertainties in such recourse problems is through two-stage stochastic programming (TSP). The fundamental idea behind the TSP is the concept of recourse, which is the ability to take corrective actions after a random event has taken place. In TSP, decision variables are divided into two subsets: those that have to be determined before the random uncertainties are disclosed and those (recourse variables) that can be determined after the uncertainties are available [30,31]. However, TSP has difficulties in dealing with uncertain parameters when their probabilistic distributions are not available; besides, the increased data requirements for specifying the parameters' probability distributions may affect their practical applicability. Fuzzy programming (FP) is suitable for situations when the uncertainties could not be expressed as probability distributions, such that adoption of fuzzy membership functions becomes an attractive alternative. Introducing interval parameters into FP framework, interval-fuzzy programming (IFP) method incapable of tackling uncertainties presented as both interval values and fuzzy sets.

Therefore, the objective of this study is to develop an integrated optimization modeling approach for carbon dioxide (CO_2) emission trading, coupling two-stage stochastic programming (TSP) with interval-fuzzy programming (IFP) to deal with uncertainties presented in terms of fuzzy sets, interval values, and random variables. A case study of an electric-power system (EPS) planning will be provided for illustrating the applicability of the developed method, where both emission trading and clean-energy development projects are employed to mitigate CO_2-emissions for three fossil-fueled power plants (i.e., gas, oil and coal-power plants). The results are helpful for managers in not only making decisions regarding electricity generation and CO_2-emission based on greenhouse gas control but also gaining insight into the tradeoff between economic objective and emission trading scheme under multiple uncertainties.