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A dynamic model to optimize municipal electric power systems by considering carbon emission trading under uncertainty

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A B S T R A C T

In this study, a FFSP (full-infinite fuzzy stochastic programming) method is developed for planning MEPS (municipal electric power systems) associated with GHG (greenhouse gas) control under uncertainty. FFSP can deal with multiple uncertainties presented in terms of fuzzy sets, functional intervals, and random variables. FFSP is also applied to a case study of Beijing for managing MEPS, and reducing the GHG emission through introducing the EU ETS (European Union greenhouse gas emission trading scheme). The results indicate that reasonable solutions have been generated, which can be used for generating schemes of energy resources, electricity production/allocation, and capacity expansion under various economic costs and GHG reduction requirements. The case study demonstrates that FFSP can increase the abilities of reflecting complexities for dynamics of capacity expansion and interaction of multiple uncertainties in MEPS. The results allow in-depth analyses of trade-offs between GHG mitigation and economic objective as well as those between system cost and decision makers' satisfaction degree. Besides, this study can also provide an example to help China construct domestic carbon trading market at municipal scale for addressing the challenges of global climate change.

1. Introduction

The increasing threat of global warming and climate change has been a major on-going concern since the 1990s. This is caused primarily by the increases of GHG (greenhouse gases) such as carbon dioxide (CO_2), and energy consumption and production are at the centre of climate change debates [1,2]. Human activity has caused an imbalance in the natural cycle of the greenhouse effects and the related processes. Particularly, MEPS (municipal electric power systems) make a significant contribution to the global GHG emission levels, such as fossil fuel burning releasing CO_2 into the atmosphere [3–5]. Since the beginning of the Industrial Revolution, the burning of fossil fuels has contributed to approximately 40% increment in the concentration of CO_2 in the atmosphere from 280 ppm to 397 ppm [6]. In addition, according to recent IEA report (2007), the world energy demand is growing at a rate of about 1.6% per year, and is expected to reach about 700×10^{18} J/Y by 2030, while more than 80% of worldwide primary energy production still coming from combustion of fossil fuels [7]. More robust approaches that can help maintain local/regional GHG emission of MEPS at a safe level are desired.

CET (Carbon emission trading) is widely considered to be one of the most effective means for GHG reduction [8,9]. Therefore, a number of research efforts were conducted for GHG mitigation in MEPS through CET scheme. However, with rapid economic development, continual urban expansion, and life standard improvement, MEPS planning is a challenging issue for decision makers. In the past decades, many research efforts were conducted for planning energy systems at various scales with consideration of CET scheme [10–15]. For example, Cormio et al. [10] introduced a bottom-up energy system optimization model for planning the use of renewable energy sources of the Apulia region in the Southern Italy. Fleten and Kristoffersen [11] developed a multistage stochastic mixed-integer programming approach for planning a price-taking hydropower plant operating under uncertainty; with the

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increase of population and the development of energy industry, contradiction of energy supply and demand was more intense in developing countries; compared to the developed countries (e.g., United States, Canada, Germany, and Japan), developing countries have backward MEPS, which needed to pay more efforts in managing MEPS for mitigation energy shortages, control air pollution, and implement carbon reduction policies. Sinha and Dudhani [12] presented linear programming for allocating optimal share of renewable energy resources with varying technological and cost coefficients, where the role of government and private agencies in promoting the growth of small hydropower was discussed. Sadeghi and Hosseini [13] used fuzzy linear programming approach for planning energy systems in Iran, where uncertainties of investment costs in objective function coefficients were taken into account.

Uncertainty plays an important role in emission trading programs in the MEPS. For example, CO_2 discharged from various electricity-generation activities (e.g., power plant, storage hydroelectric plant, or biomass power plant) can be influenced by some uncertain events (e.g., emission limitation), which may fluctuate time to time [16,17]. Meanwhile, errors in estimated modeling parameters (e.g., economic penalty) could be possible sources of uncertainties. These complexities have placed many electric power systems management problems beyond the conventional optimization methods. It is thus necessary to develop effectively optimization methods for planning CET in MEPS under various complexities and uncertainties. For instance, Rong and Lahdelm [18] proposed a multi-period stochastic optimization method combined with heat and power production to plan CET. In this study, uncertainties were represented as stochastic parameters. Soimakallio et al. [19] studied GHG balances of transportation biofuels, electricity and heat generation in Finland, while uncertainties expressed as probability distribution. Sadegheih [20] described an adaptation of optimization models under CET program, while uncertainty parameters expressed as discrete form. Zhou et al. [21] developed a FIPP (fuzzy-interval possibilistic programming) method is for supporting municipal electric power system planning for the City of Shenzhen with carbon emission abatement through clean development mechanism, where systematic uncertainties expressed as crisp intervals and fuzzy-boundary intervals were effectively tackled.

Among the above methods, TSP (Two-stage stochastic programming) is effective for problems where an analysis of policy scenarios is desired and when the right-hand-side variables are random with known probability distributions. In TSP, the first-stage decision is to be confirmed before uncertain information is revealed, whereas the second-stage one (economic recourse) is to adapt to the previous decision based on the further information [22]. However, the increased data requirements for specifying the parameters' probability distributions can affect the practical applicability of TSP. IPP (Interval-parameter programming) approach is an alternative for handling uncertainties expressed as interval numbers that exist in model's objective function and constraints. IPP allows uncertainties to be directly communicated into an optimization process and resulting solutions; it also does not lead to more complicated intermediate models, and thus has a relatively low computational requirement [23]. In an IPP model for energy system planning, cost for energy sources expressed as $[a, b]$ US dollar per unit. The $[a, b]$ is a set of real numbers, where $[a, b]$ means that energy cost would range from a to b. Nevertheless, IPP has difficulties when the lower and upper bounds of an interval number are not deterministic (i.e. functional interval values).

An attractive technique that could tackle functional interval values was FIP (full-infinite programming) [24]. In fact, the conventional IPP can only solve the problems containing crisp interval coefficients $[a, b]$, whose lower and upper bounds (i.e. a and b) are both deterministic and definitely known. This is based on the assumption that these interval coefficients are unchanged even if they could be affected by associated impact factors. In actual systems, this definition is not suitable for all cases where the two bounds may be associated with the external impact factors. For example, in electric power systems planning problems, if the energy purchased cost is affected by the interest rate, the lower and upper bounds can vary since any variation in interest rate will lead to a corresponding change in energy purchased cost. Therefore, the concept of crisp interval may not be suitable for describing such an uncertainty. An effective way of describing this uncertainty is functional intervals; this can be defined as a lower and an upper bound, which are both functions of its associated impact factor. For example, in MEPS planning problems, if the energy purchased cost (CN) is affected by the interest rate, the lower and upper bounds can vary since any variation in interest rate will lead to a corresponding change in *CN*. Therefore, the concept of crisp interval may not be suitable for describing such an uncertainty. An effective way of describing this uncertainty is functional intervals; this can be defined as a lower and an upper bound, which are both functions of its associated impact factor. For example, if *CN* is expressed as a functional interval of $[25.33(1+\alpha)^t, 26.20(1+\alpha)^t] \times 10^6$ US$/PJ; the α and t denote the interest rate and interval in each period time, CN is a function of interest rate, ranging between $25.33(1+\alpha)^t \times 10^6$ US$/PJ and $26.20(1+\alpha)^t \times 10^6$ US$/PJ.

Besides, from a long-term planning point of view, electricity demand and supply will increase in response to population growth, economic development, and life standard improvement. This tendency could often result in insufficient capacities of power-generation facilities to meet the overall electricity demand. IMILP (Inexact mixed integer linear programming) technique is a useful tool for capacity expansion planning under uncertainty [25]. In addition, it is worthy to mention that the purpose of formulation of optimized model is to maximize satisfaction degree of the planning system, but this degree is ambiguity and vagueness. FLP (Fuzzy linear programming) is an effective technology for obtaining maximized membership grades (satisfaction degree) corresponding to the degrees of overall satisfaction for the constraints and objective [26]. Therefore, the objective of the study is to develop a FFSP (full-infinite fuzzy stochastic programming) method for planning the MEPS by controlling CO_2 emission under multiple uncertainties. Uncertain parameters are expressed as fuzzy sets, functional intervals, and random variables, such that robustness of the optimization effort will be enhanced. Furthermore, it can support the analysis of various policy scenarios which have different levels of economic penalties when the promised targets are violated. Then, a case study of planning CET of Beijing's MEPS will be provided for illustrating the applicability of the developed method. The results will help decision makers gain insights into the tradeoffs between economic objective and CO_2 mitigation scheme.

2. Modeling formulation

Beijing, as the capital of China, has a rapid growth in energy demand due to economic development and population growth in the recent decades; the city's total electricity consumption reached 85.39 billion kWh in 2011 [27]. Around 70% of the city's electricity needs to be transferred from the neighboring provinces. Beijing launched the National Climate Change Program and released a white paper on its climate change policy responses in 2007 and 2008 respectively [28,29]. Centrally planned policy guidelines are published in a periodic legislative document known as the “Five-Year Plan for National Economic and Social Development”. Major administrative units and local governments then formulate their own Five-Year Plans in line with national directions. The idea of