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Full-infinite interval two-stage credibility constrained programming for electric power system management by considering carbon emission trading

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ABSTRACT

In this study, a full-infinite interval two-stage credibility constrained programming (FITCP) method is developed for optimizing electric power system (EPS) by considering CO_2 mitigation and air pollutant emission control. Through integrating full-infinite programming (FIP), interval two-stage programming (ITSP) and credibility constrained programming (CCP) within a general framework, the developed FITCP method can tackle multiple uncertainties in terms of interval values (both crisp and functional interval values), probabilistic and possibilistic distributions. Then, a FITCP-based electric power system (FITCP-EPS) model has been formulated for EPS planning where carbon emission trading (CET) scheme and air pollutant emission limitation are introduced to cope with the problem of carbon and air pollutant mitigation. Scenarios in response to diverse carbon mitigation levels, different trading schemes and different environmental policies are generated. Moreover, sensitive analysis and value of information analysis are conducted to help decision makers to have a clear view of the effects of data variation and uncertainty data collection. Results reveal that (i) CET scheme can bring more economic benefits for power plants especially when mitigation level is high; (ii) whether the CET is carried out or not, a corresponding construction of carbon capture and storage infrastructure should be implemented to achieve the mitigation target; (iii) the expected system benefit would increase [0, 2.17] % by resolving the uncertainty of CO_2 emission levels. The results also indicate that FITCP-EPS model can not only provide an effective linkage between the pre-regulated generation targets and environmental policies, but also generate more decision options under different credibility levels and CO_2 emission levels, which are useful for helping decision makers to make appropriate generation targets, plan electricity generation mix, as well as gain in-depth insight into the effects of carbon emission trading and pollutant control on EPS.

1. Introduction

The issues of global warming and climate change have been a universal concern since the 1990s, which are caused primarily by the increasing of greenhouse gases (GHGs) emissions [15,44,3,35]. As the main contributor of GHGs, carbon dioxide (CO_2) emission increased to 32.3 billion tonne in 2014 and is expected to break 40 million tonne in 2035 with the increasing of fossil fuels' consumption [48,20]. Negative impacts of CO_2 on environment and climate force decision makers to take effective measures to achieve CO_2 mitigation towards sustainable ways. Carbon emission trading (CET), which offers flexibility via a market mechanism rather than compulsory regulations, has been widely implemented for controlling CO_2 emission [34,36]. In the market-oriented CET scheme, CO_2 emission permits are first allocated based on the actual historical emissions or carbon emissions baseline set by the government. After the flexible trading between emitters, the CO_2 emission permits have a reallocation, and the permits are assigned to the most efficient emitters rather than proportionally allocated to each emitter [23,22]. Because of the massive energy consumption, the power sector becomes the most important source of carbon emissions, accounting for over a third of energy consumption emissions in 2017 [5]. Therefore, electric power system (EPS) is at the center of CO_2 mitigation debates, and it is of vital importance to investigate the impacts of CET on CO_2 mitigation for EPS [37].

However, an EPS with CET scheme is often associated with many complex processes such as fuel supply, electricity generation, electricity transportation, electricity selling, capacity expansion, carbon permits allocation, carbon capture and storage (CCS) and carbon trading [2,14]. Moreover, in a regional EPS, there are complicated uncertain factors associated with economic and technique parameters (electricity price,

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fuel cost, operation cost, expansion cost, etc.), as well as vague information related to CO_2 and environmental policy, which compounds the difficulties of EPS planning [6,43,41]. In the past decades, a number of optimization methods were proposed to deal with interrelated complexities and uncertainties of EPS, mainly based on interval-parameter programming (IPP) and two-stage stochastic programming (TSP). For example, Chen et al. [8] developed an interval two-stage stochastic programming method for planning CO_2 emission trading under uncertainty, where uncertainties in electricity demand and supply index were expressed as probabilistic distributions. Tajeddini et al. [42] formulated a TSP model for planning the GenCo system under stochastic uncertainties. Wu et al. [46] proposed a TSP model for managing electric vehicle charging in a distribution system with uncertainty in EV arrival times and charging demands upon arrival. Nojavan et al. [31] put forward IPP for the optimal management of hydrogen storage systems and plug-in electric vehicles in the scheduling of retailer under inexact market price uncertainty. Ordoudis et al. [33] developed a TSP model for electricity and natural gas systems management under stochastic renewable energy production.

Among these methods, interval two-stage stochastic programming (ITSP) method, incorporated interval-parameter programming (IPP) and two-stage stochastic programming (TSP), is a potential approach for electric power planning and receive much attention [52]. ITSP method is not only capable of reflecting uncertainties in terms of crisp interval values and known probabilistic distributions, but also effective in achieving management strategy adjustment after real events happened [7,32,4]. Moreover, ITSP method could provide an effective linkage between the pre-regulated generation targets and environmental policies [38,30]. In EPS planning, one problem of ITSP is its inefficiency in treating functional intervals whose lower and upper bounds are affected by external factors. For example, energy purchasing cost, which is associated with energy demand and supply index, is not crisp value since any change in energy demand and supply index may result in its corresponding variation [27]. Thus, the energy purchasing cost can be expressed as functional interval value (e.g. [2.08 + 0.16η, 2.10 + 0.16η], the η denotes the energy demand and supply index) [12,11,39,9,28,10].

Previously, numerous inexact programming approaches have been conducted for handling such uncertainties. For instance, He et al. [16] developed an interval full-infinite programming method for solid waste system management which could effectively deal with uncertainties expressed as interval values and functional intervals. Zhu et al. [54] proposed a full-infinite interval-stochastic mixed-integer programming method to cope with functional and crisp interval uncertainties of economic parameters in EPS of Beijing. Jin et al. [21] developed a superiority–inferiority full-infinite mixed-integer programming method for analyzing the effect of energy conversion efficiency; in this study, the economic parameters are described as functional intervals that varied with the interest rate. Simic et al. [38] proposed an interval-parameter two-stage stochastic full-infinite programming model for end-of-life vehicles allocation management, where the minimum quantities of ELVs that must be allocated to vehicle recycling factories were presented as functional intervals associated with the shredding rates. Generally, full-infinite programming (FIP) method is effective for dealing with uncertainties described as functional interval value existing in both objective functions and constraints. With incorporating FIP and ITSP into a general framework, a full-infinite interval two-stage programming (FITP) method is developed for handling uncertainties expressed as probabilistic distributions, crisp and functional interval values.

However, in the real-world EPS problems, fuzzy uncertainties from ambiguity and vagueness of human judgments are often involved in decision-making processes [24,29]. For example, the environmental policies (e.g., the amount of pollutant emission limitation) are often determined based on decision makers' subject judgments. Thus, uncertainties in related environmental parameters can be expressed as possibilistic distributions, which cannot be tackled by the FITP method. Credibility constrained programming (CCP), initially introduced by Liu, is a powerful tool for addressing uncertainties in format of possibilistic distributions [25]. CCP method has been applied to many real-world cases because of its efficiency in reflecting the fuzziness in parameters (e.g., environmental policies and standards) associated with subjective considerations [24]. Nevertheless, CCP method has limitations in tackling uncertain parameters that exist in the model's left-hand sides and coefficients, and reflecting the random characteristics in EPS (e.g. carbon emission levels) [52]. Therefore, a more effective method is desired for reflecting the fuzziness in parameters, as well as handling uncertainties described as probabilistic distributions, crisp and functional interval values.

The objective of this study is developing a full-infinite interval two-stage credibility constrained programming (FITCP) method for supporting CO_2 and air pollutant mitigation of EPS. Through integrating optimization techniques of ITSP, FIP and CCP within a general framework, the developed FITCP method can deal with uncertainties described as probabilistic distributions, crisp and functional interval values as well as possibilistic distributions. A FITCP-based electric power system (FITCP-EPS) model is formulated for EPS planning where carbon emission trading (CET) scheme and air pollutants emission limitation are introduced to cope with the problem of carbon and air pollutant mitigation. A series of scenarios corresponding to diverse CO_2 emission mitigation plans, different trading schemes and varied credibility levels of environmental policies are analyzed to investigate the impacts of CET and carbon mitigation on electricity generation mix, carbon and pollutants emissions as well as system cost. The results can help decision makers to restructure electricity generation mix and gain insight into the effects of carbon emission trading and pollutant control on EPS under multiple uncertainties.

2. Methodology

2.1. Formulation of FITCP

Interval two-stage stochastic programming (ITSP) is effective for addressing problems where an analysis of policy scenarios is desired periodically over time and uncertainties in input data are expressed as probabilistic distributions and crisp interval values. The ITSP framework can be formulated as follows [47]:

$$\text{Max } f^{\pm} = \sum_{i=1}^{N} c_i^{\pm} x_i^{\pm} - \sum_{i=1}^{N} \sum_{h=1}^{M} p_h Q_i^{\pm} y_{ih}^{\pm} \tag{1a}$$

subject to:

$$A_i^{\pm} x_i^{\pm} - y_{ih}^{\pm} \leqslant B_i^{\pm} \tag{1b}$$

$$X_{i\,\min} \leqslant x_i^{\pm} \leqslant X_{i\,\max} \tag{1c}$$

$$x_i^{\pm} \geqslant 0,\ \ y_{ih}^{\pm} \geqslant 0. \tag{1d}$$

where $x_i^{\pm}$ and $y_{ih}^{\pm}$ are the first- and second-stage decision variables, respectively; $\sum_1^N c_i^{\pm} x_i^{\pm}$ is the first-stage benefits; h represents the scenario of the random event; p_h is probability level and $\sum p_h = 1$; $\sum_1^N \sum_1^M p_h Q_i^{\pm} y_{ih}^{\pm}$ is expected value of the second-stage system penalties; $A_i^{\pm}$ and $B_i^{\pm}$ are constraints' coefficients; $X_{i\,\min}$⩽ and $X_{i\,\max}$ are minimum and maximum value of $x_i^{\pm}$; the '+' and '−' superscripts represent lower and upper bounds of an interval parameter/variable, respectively. The ITSP method can deal with uncertainties described as probabilistic distributions and interval values whose lower and upper bounds are definitely known. Nevertheless, it has difficulty in solving functional interval values (i.e. lower and upper bounds are functions instead of crisp values). Full-infinite programming (FIP) method is a powerful tool for dealing with uncertainties described as functional interval values. When incorporating FIP and ITSP methods into a general framework, a