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An optimization model design for energy systems planning and management under considering air pollution control in Tangshan City, China

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ABSTRACT

In this study, an interval-parameter fuzzy programming mixed integer programming method (IFMIP) is designed for supporting the planning of energy systems management (ESM) and air pollution mitigation control under multiple uncertainties. The IFMIP-ESM model is based on an integration of interval-parameter programming (IPP), fuzzy programming (FP), and mixed-integer programming (MIP), which can reflect multiple uncertainties presented as both interval values and fuzzy distributions numbers. Moreover, it can successfully identify dynamics of capacity expansion schemes, reflect dual dynamics in terms of interval membership function, and analyze various emission-mitigation scenarios through incorporating energy and environmental policies. The designed model is applied to a case of energy systems management in Tangshan City, China, and the results indicate that reasonable solutions obtained from the model would be helpful for decision makers to effectively (a) adjust the allocation patterns of energy resources and transform the patterns of energy consumption and economic development, (b) facilitate the implement of air pollution control action plan, and (c) analysis dynamic interactions among system cost, energy-supply security, and environmental requirement.

1. Introduction

Over the past decades, energy consumption has been rising at an alarming rate; as a result, the contradiction between energy supply and demand is increasingly prominent. What's more, the coal-dominated energy structure leads to a large number of environmental problems in China; air pollution has become a pressing issue for socio-economic development and public health. The aggravating energy crisis and increasing environmental concerns have forced decision makers to identify comprehensive plans at multiple scales for energy system management [1–5]. However, many processes associated with various complexities need to be considered in energy system, such as energy exploitation, import/export, conversion, transportation, consumption, as well as the related air pollutant emission control [6]. Additionally, many parameters are characterized by a variety of elements involved with multiple forms of uncertainties, such as electricity and heat demands, technology efficiencies, and energy availabilities, which have further complicated the complexities in energy system management. Therefore, it is desired to design an effective analysis approach to support energy system management considering dynamic balance between energy development and environmental quality under uncertainty.

Previously, many innovated optimization methods had been extensively applied to energy system management problems [2,7–9]. For example, Khella advanced an energy model associated with analyzing policies between energy utilization and environmental costs, which could identify alternative energy policies and strategies for minimizing economic costs and environmental loss [7]. The relationships between carbon dioxide emissions and energy consumptions of 17 countries were studied by Ramanathan [9]. However, these studies could be hardly incapable of reflecting the complicated interactions among different energy activities and the associated socio-economic, environmental, technical, and political impacts. In addition, many processes related to energy system management were not effectively addressed in these studies, such as the facility expansion linked to the issues of timing and sizing [10]. Moreover, it was still difficult to

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effectively tackle these uncertainties coupled with the dynamic feature of system conditions (e.g., temporal and spatial variations of system factors).

As an extension for solving the above limitations, a significant amount of inexact optimization approaches were proposed for energy system management for the sake of handling various uncertainties [11–15]. For example, on the base of inexact fuzzy chance-constraint programming, Hu et al. advanced a method of lower-side attainment degrees to support regional electric power system management under complex situations [13]. Kanudia and R. Loulou developed a multi-stage stochastic programming strategy to create a flexible energy plan that took into consideration climate change and economic growth factors [14]. Peck and Teisberg proposed a stochastic programming method to address uncertainties with known probability density functions and applied it to the global energy systems planning [15]. Among those approaches, interval-parameter programming (IPP) approach is an available tool for tackling uncertainties presented as interval values without known distributions information and membership functions, existing in model's objective function and system constraints [16]. In addition, integer programming (IP) is effective for dealing with dynamic issues such as location selection, technique selection, capacity expansion, and emission allocation, where integer variables will be required to indicate whether or not particular decision should be made. The integration of IPP and IP approaches would lead to an interval-parameter mixed-integer programming (IMIP) which allows uncertainties presented as interval numbers to be conveyed into the integer optimization process and resulting solutions. IMIP was successfully applied to municipal solid waste planning, water resources analysis, air quality management and so on [17–19]. For example, Zhu et al. advanced an interval full-infinite mixed-integer programming method for planning municipal energy systems of Beijing [20]. Nevertheless, IMIP method might be infeasible when the model's right-hand side coefficients are highly uncertain, which will restrict its usefulness in practical applications. Moreover, it has difficulties in solving multiple uncertainties inset with an individual parameter (e.g., the lower and upper bounds of interval values are not both deterministic values and definitely known).

The relevant fuzzy programming can effectively deal with decision problems under uncertainties presented as possible distributions in the system objective and constraints with ambiguous coefficients and vague information. It allows the uncertain aspects of a model's right-hand sides (e.g., resources availability) to be expressed as fuzzy sets. In addition, it can delimit an uncertain decision space to these uncertainties through enlarging the original fuzzy constraints dimensionally [21,22]. For example, Li et al. proposed a fuzzy-stochastic programming approach for energy and environmental systems planning under uncertainty [23]. Muela et al. developed a fuzzy possibilistic model for power generation planning that included environmental criteria [24]. Considering the coefficients of investment costs in the objective function with various uncertainties, Sadeghi and Hosseini presented a fuzzy linear programming method for energy systems management in Iran [25]. However, the fuzzy programming may encounter limitations when it handles multiple uncertainties in the constraints of the model's left-hand-sides. Meanwhile, IPP is an effective procedure to deal with multiple uncertainties in a model's left-hand-sides, but fails to solve difficulties when the right-hand-sides are highly uncertain. Therefore, one potential approach for better handling the uncertainties in energy system is to combine the IMIP and FP methods within a general model framework. In general, uncertain input parameters in the model framework are estimated by discrete intervals; nevertheless, it will generate a dual uncertainty into the parameters when the lower and upper bounds of these interval numbers may also be not known. For example, the lower and upper bounds of available renewable resources presented as discrete interval numbers may also not be described by a certainty value, this will lead to dual uncertainties problem for the availabilities of renewable resources. Nevertheless, few previous studies were focused on the dual uncertainties in energy system management.

Therefore, based on previous research efforts, the objective of this study is to develop an interval-parameter fuzzy programming mixed integer programming method (IFMIP) for supporting regional energy system management coupled with air pollution control under multiple uncertainties. The method techniques of interval-parameter programming (IPP), fuzzy programming (FP) and mixed-integer programming (MIP) will be incorporated within a general optimization framework. It can not only tackle uncertainties presented as discrete interval numbers and fuzzy membership functions in the model's objective function and constraints, but also can reflect dual dynamics in terms of interval membership function where the former research had barely considered. The designed model will be applied to a case of energy system management under considering air pollution control in Tangshan City, China. The results can help decision makers not only acquire more reasonable decision alternatives and applicable solutions, but also gain deep insights into the tradeoffs between system cost and environmental objective when it comes to decide which final management strategies to choose. In detail, the solutions obtained in this study can successfully (a) identity the complex linkage among the entire energy system (e.g., energy exploitation, conversion, transportation, consumption etc.), (b) tackle multiple uncertainties expressed as intervals and fuzzy membership functions among various parameters, sectors and processes of energy system management, (c) reveal some issues and phenomena about energy development in Tangshan, (d) facilitate dynamic analysis for allocation patterns of energy supply, electricity, heat, and processing, as well as facility expansion schemes under air pollution mitigation plans.

2. Methodology

2.1. Interval parameters programming

Interval parameters programming model (IPP) is an effective method for handling uncertainties expressed as interval numbers without known distribution information, which can be expressed as follows [16]:

$$\min f^{\pm} = C^{\pm}X^{\pm} \tag{1a}$$

subject to:

$$A^{\pm}X^{\pm} \le B^{\pm} \tag{1b}$$

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