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Integrated modeling approach for sustainable municipal energy system planning and management – A case study of Shenzhen, China

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A B S T R A C T

In this study, a fractile-based interval mixed-integer programming (FIMP) method is advanced for sustainable municipal-scale energy system planning and management. FIMP can handle uncertainties presented in terms of fuzzy boundary intervals that represent interval coefficients with independently fuzzy lower and upper bounds with possibility distributions. A FIMP-based municipal energy model (FIMP-MEM) is then formulated for managing various energy activities in the City of Shenzhen, China. Solutions for energy supply, electricity generation, oil-product production, air-pollutant mitigation, carbon dioxide control, capacity expansion, and electricity import/export are obtained. Results can be used to help the city's managers to identify desired system designs and to determine which of these designs can most efficiently accomplish optimizing the system objective under diverse *p*-necessity fractiles. The generated decision alternatives are beneficial for the city's energy system planning and management through (a) generating desired energy resources allocation, (b) identifying electricity generation and capacity-expansion scheme, (c) providing air pollution control plan, (d) analyzing the tradeoff among system cost, environmental impact, and system-failure risk.

1. Introduction

Sustainable municipal energy systems planning and management are able to assist decision makers with effective goal settings and policy formulations in the energy planning procedure through integrating environmental, economic and social dimensions (IAEA, 2005; Rad, 2011). It is implemented to optimize energy consumption structure as well as achieve sustainable development mode. Currently, many countries (e.g., China) primarily rely on fossil fuels to meet the ever-increasing energy demand. However, owing to over exploitation of fossil fuels, fossil fuel-based energy consumption structure has given rise to a series of disastrous consequences, such as resources shortage, air pollution, and climate change (EH&E, 2011). Annual global emissions of air pollutants and greenhouse gases resulting from fossil-fuel combustions are undergoing soaring and continuous increment. Consequently, a large number of researchers endeavor to seek for effective techniques to support decisions of energy system planning and environmental management in responses to such challenges (Zhang and Hua, 2007; Kadian et al., 2007; Tan et al., 2009; Zvingilaite, 2011; Shen et al., 2012; Leduc and Van Kann, 2013; Suo et al., 2013).

In the real-world energy system management problems, complexities may occur in various impact factors (e.g., financial, technical, environmental and political) and energy-related processes (e.g., exploration/exploitation, processing/conversion, transmission/allocation, and supply/demand), which may have great influences on related optimization analysis and relevant decision making. The inherent complexities and uncertainties in energy system have made conventional deterministic optimization techniques fall into a dilemma. Consequently, massive researchers focused on developing fuzzy mathematical programming methods for planning and managing energy system to achieve the optimal energy-allocation scheme, minimal environmental emission and minimized economic cost (Muela et al., 2007; Zhang and Rong, 2010; Tan, 2011; Lotfi and Ghaderi, 2012). Fuzzy possibilistic programming (FPP) is effective for representing the possible degree of event occurrence for imprecise data described by fuzzy possibility distributions (Inuiguchi and Ramik, 2000). Nevertheless, the traditional FPP may encounter limitations when many parameters

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are presented as fuzzy sets, where interactions among these uncertain parameters may result in serious system complexities (e.g., complicated intermediate models and increased computational requirements) that are not applicable to large-scale practical problems.

In fact, in energy system planning problems, various uncertainties exist in both objective function (e.g., fluctuating electricity price, imprecise fuel cost) and system constraints (e.g., uncertain energy and electricity demands, changed environmental emissions); furthermore, dual uncertainties may exist within one parameter in the objective function. For example, owing to the intrinsic fluctuations of factors (e.g., cash flow, and energy price), cost parameters are often estimated by energy experts with interval values and, at the same time, their lower and upper bounds of these intervals may be provided as subjective judgments from a number of decision makers (e.g., expressed as possibility distributions). The conventional FPP may become infeasible in handling such uncertainties. Interval-parameter programming (IPP) is an attractive technique and could effectively address interval values without any distribution information; however, IPP has difficulties in tackling uncertainties presented as possibility distributions (Nie et al., 2007; Huang and Cao, 2011; Fan and Huang, 2012).

Therefore, the objective of this study is to advance a fractile-based interval mixed-integer programming (FIMP) method for municipal-scale energy system planning and management. FIMP incorporates FPP and IPP, such that uncertainties presented in terms of fuzzy boundary intervals in the objective function can be tackled. A FIMP-based municipal energy model (FIMP-MEM) is then formulated for managing and planning energy activities in the City of Shenzhen, which is situated in the south of Guangdong Province of southern China. Solutions for energy supply, electricity generation, oil-product production, air-pollutant mitigation, carbon dioxide control, capacity expansion, and electricity import/export will be obtained; they can help further generate decision alternatives with diverse p-necessity fractiles for the adjustment of Shenzhen's existing energy allocation patterns, local policies formulation associated with energy consumption and system management, and long-term Shenzhen's sustainable energy system planning.

2. Methodology

When uncertainties are expressed as possibility distributions in the ambiguous coefficients of objective function, it can be treated as a FPP model (Zadeh, 1978):

$$\text{Min } \underset{\sim}{f} = \underset{\sim}{C}X \tag{1a}$$

subject to:

$$AX \geq B \tag{1b}$$

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

where coefficient $\underset{\sim}{C}$ represents the fuzzy possibilistic variable with possibility distribution. Model (1) is effective for handling the uncertainties described by possibility distributions. Nevertheless, in practical municipal energy system planning and management, cost estimation may be mostly based on experience and expertise. Under such circumstance, cost parameters in the objective function can rarely be acquired as deterministic possibility distributions; instead, they may often be collected as discrete intervals with lower and upper bounds (Li et al., 2011). Namely, interval values of cost parameters may fluctuate with their bounds being available as subjective preferences from decision makers, which may be provided by fuzzy possibility distributions. These result in dual uncertainties presented as fuzzy boundary intervals in the system components (Nie et al., 2007). IPP approach is conducive to tackling the uncertainties expressed as crisp interval values in objective function and constraints without probability distributions and membership functions (Fan and Huang, 2012). Therefore, coupling IPP with FPP, a fractile-based interval mixed-integer programming (FIMP) model can be formulated as follows:

$$\text{Min } \underset{\sim}{f}^{\pm} = \sum_{j=1}^{k} \underset{\sim}{c}_j^{\pm} x_j^{\pm} + \sum_{j=k+1}^{n} \underset{\sim}{c}_j^{\pm} x_j^{\pm} \tag{2a}$$

subject to:

$$\sum_{j=1}^{k} a_{ij}^{\pm} x_j^{\pm} + \sum_{j=k+1}^{n} a_{ij}^{\pm} x_j^{\pm} \leq b_i^{\pm}, i = 1, 2, \ldots, m \tag{2b}$$

$$x_j^{\pm} \geq 0, \; j = 1, 2, \ldots n \tag{2c}$$

where $a_{ij}^{\pm} \in \{R^{\pm}\}^{m \times n}$, $b_i^{\pm} \in \{R^{\pm}\}^{m \times 1}$, $\underset{\sim}{c}_j^{\pm} \in \{R^{\pm}\}^{1 \times n}$, $x_j^{\pm} \in \{R^{\pm}\}^{n \times 1}$; $R^{\pm}$ mean a set of interval numbers; $x_j^{\pm}$ denote decision variables that are divided into two categories: continuous and binary variables; $\underset{\sim}{c}_j^{\pm}$ $(j = 1, 2, \ldots, k)$ and $a_{ij}^{\pm}$ $(j = 1, 2, \ldots, k)$ show positive coefficients; $\underset{\sim}{c}_j^{\pm}$ $(j = k+1, k+2, \ldots, n)$ and $a_{ij}^{\pm}$ $(j = k+1, k+2, \ldots, n)$ imply negative coefficients; $\underset{\sim}{c}_j^{\pm}$ represent interval coefficients with independently fuzzy lower and upper bounds with possibility distributions, named fuzzy boundary intervals. Since the triangular fuzzy membership function is the most popular possibility distribution, it is utilized to reflect such uncertainty in this study. A symmetric triangular fuzzy number $\underset{\sim}{C}$ is considered, which can be determined by a center c^c and a spread w, and can be described as $\underset{\sim}{C} = (c^c, w)$. In model (2) [e.g., Equations (2a)–(2c)], since imprecise coefficients of the objective function are all restricted by symmetric triangular fuzzy numbers $\underset{\sim}{c}_j^{\pm} = (c_j^{c\pm}, w_j)$ and $\underset{\sim}{c}_j'^{\pm} = (c_j'^{c\pm}, w_j')$, j = 1,2,…,n, the linear objective function (also called possibilistic linear function) is also of fuzzy feature and its function value $\underset{\sim}{f}$ which restricts $\underset{\sim}{f}^{\pm} = \sum_{j=1}^{k} \underset{\sim}{c}_j^{\pm} x_j^{\pm} + \sum_{j=k+1}^{n} \underset{\sim}{c}_j^{\pm} x_j^{\pm}$ is also a symmetric triangular fuzzy number based on the extension principle as follows (Inuiguchi and Ramik, 2000):

$$\underset{\sim}{f}^{\pm} = \left(\sum_{j=1}^{k} c_j^{c\pm} x_j^{\pm} + \sum_{j=k+1}^{n} c_j'^{c\pm} x_j^{\pm}, \sum_{j=1}^{k} w_j \left| x_j^{\pm} \right| + \sum_{j=k+1}^{n} w_j' \left| x_j^{\pm} \right| \right) \tag{3}$$

Thus, the objective function of model (2) [e.g., Equation (2a)] is equivalent to:

$$\text{Min} \underset{\sim}{f}^{\pm} = \left(\sum_{j=1}^{k} c_j^{c\pm} x_j^{\pm} + \sum_{j=k+1}^{n} c_j'^{c\pm} x_j^{\pm}, \sum_{j=1}^{k} w_j \left| x_j^{\pm} \right| + \sum_{j=k+1}^{n} w_j' \left| x_j^{\pm} \right| \right) \tag{4}$$

Based on the necessity measure in the possibility theory, fractile approach is introduced to solve above objective of minimizing a symmetric triangular fuzzy number (Zhou et al., 2013). Thus, through minimizing the p-necessity fractile of a possibilistic variable $\underset{\sim}{f}^{\pm}$, Equation (4) can be converted into the following defuzzification expression:

$$\text{Min} \left(\sum_{j=1}^{k} c_j^{c\pm} x_j^{\pm} + \sum_{j=1}^{k} p_{\text{nes}} w_j \left| x_j^{\pm} \right| + \sum_{j=k+1}^{n} c_j'^{c\pm} x_j^{\pm} + \sum_{j=k+1}^{n} p_{\text{nes}} w_j' \left| x_j^{\pm} \right| \right) \tag{5}$$