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Inexact mixed-integer programming with interval-valued membership function for sustainable power-generation capacity planning

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ABSTRACT

In this study, inexact mixed-integer linear programming with interval-valued membership function (IMILP-IMF) is developed for power-generation capacity planning. IMILP-IMF can deal with uncertainties described as fuzzy sets with interval-valued membership function, and allows uncertainties to be directly communicated into the optimization process and the resulting solution. IMILP-IMF is applied to a case study of supporting long-term planning for an electric power system (EPS). It can facilitate dynamic analysis for decisions of capacity expansion planning within a multi-facility, multi-option and multi-period context. Solutions of energy resources allocation, capacity expansion, air pollution control, and electricity generation with a minimized system cost are obtained. Results reveal that, from a long-term planning point of view, more capacities of renewable energy generation need to be installed to replace the outdated facilities to transfer the EPS to a clean, sustainable and reliable one. Results of power-generation capacity planning in association with economic consideration and environmental requirement can also help decision makers to formulate the relevant policies, optimize energy supply structure, as well as facilitate the sustainable development of electric power systems. The findings will help generate decision alternatives under multiple scenarios, and thus offer insight into the tradeoffs between economic and environmental objectives.

1. Introduction

Over the past decades, electricity demand and supply have been steadily increasing in response to population growth, economic development and life standard improvement throughout the world (Zhu et al., 2014; Brizmohun et al., 2015). According to China Electricity Council (2013), since 2013, China's installed capacity of electric power have surpassed 1247 GW, and the electricity generation of thermal power plants accounts for over 80% of the total electricity generation. Such a fossil-fuel-based energy consumption structure has given rise to a series of disastrous consequences, such as resources shortage, air pollution, and climate change (Pao et al., 2015). The increasing energy consumption and environmental pollution have raised great concern on the sustainability of China's economic growth. As a result, Chinese government has proposed a strategic objective to build a resource-conservation and environment-friendly society in order to balance the relationship among economic development, energy consumption, and environmental protection (Wu et al., 2015). Therefore, from the perspective of sustainable development, effective actions have to be taken to improve the share of renewable energy (e.g., wind, solar, biomass) to meet the increasing electricity demand and strict environmental requirement.

On the other hand, as time goes by, a significant number of facilities are old, inefficient, dirty, and no longer economically

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competitive, and they are being operated at increased costs and decreased practical capacities. According to the report (Ripe for Retirement, 2012), old coal-fired generators may lack adequate equipment to control the emissions of pollutants; they can release more harmful pollutants and damage public health. This tendency could also result in insufficient capacities of power-generation facilities to meet the overall electricity demand. For keeping up with the increase tendency of electricity demand, it is necessary for electric power systems (EPS) to expand its generation capacity. Capacity planning is a desired approach, which involves the selection of generation technology options to be added to an existing system, and when and where they should be constructed to meet the growing energy demand over a planning horizon (Neshat and Amin-Naseriis, 2015). It is implemented can optimize energy consumption structure as well as achieve sustainable development of EPS. Consequently, capacity planning for electric power is a crucial issue for sustainable development of EPS, where a related optimization analysis will typically require the use of integer variables to indicate whether a particular facility development or expansion option needs to be undertaken.

Mixed-integer linear programming (MILP) is a useful tool for capacity planning of EPS, where integer variables can be typically used to indicate whether or not particular expansion options are to be undertaken (Llorens-Iborra et al., 2012; Dai and Mesbahi, 2013; Franco et al., 2013; Barteczko-Hibbert et al., 2014). However, to accomplish the sustainability of regional electric power system, capacity planning is a multifaceted complex process. Some of the variables make such capacity planning particularly difficult, including rapidly changing demographics, environmental impacts, finite resources, policy requirements and advances in technologies (Blumberga et al., 2014; Hosnar and Kovac-Kralj, 2014; Seddighi and Ahmadi-Javid, 2015). For example, to meet the projected electricity demand, decision makers should harness the local renewable resources and employ the fossil fuel more efficiently. When existing capacity is insufficient, they have to determine the type, size, location, and commissioning time of new generating units in a planning horizon. Besides, many system parameters and their interrelationships are uncertain, due to human-induced imprecision or fuzziness, such as lack of available data and biased judgment (or preferences) in assigning priority factors (weighting levels) to multiple management objectives (Zhou et al., 2014; Hu et al., 2014; Ahmadi et al., 2015). As a result, these complexities and uncertainties place capacity planning beyond the conventional MILP methods.

Massive researchers focused on introducing inexact optimization approaches into the MILP framework to tackle capacity planning and reflect various uncertainties of EPS (Nürnberg and Römisch, 2002; Muela et al., 2007; Parpas and Webster, 2014). For example, Liu et al. (2008) developed an integrated fuzzy possibilistic-joint probabilistic mixed-integer programming model for capacity expansion planning of power plants under uncertainty, through considering increasing electricity demand, greenhouse-gas emission abatement, and explored reserve limitation. Li et al. (2010) developed an inexact fuzzy-stochastic mixed-integer programming for planning energy and environmental systems management under uncertainty, where capacity expansion schemes of each conversion technology were undertaken to avoid insufficient electricity supply under the high electricity-demand level. Balaman and Selim (2014) proposed a fuzzy multiobjective mixed-integer linear programming model for planning bioenergy plants that were used for meeting energy supply in a cost-effective and environment-friendly manner. In general, these studies were capable of reflecting dynamic complexities in energy systems. However, few studies focused on retirement of aged facilities when power-generation capacity was expanded over a long-term planning horizon. Besides, fuzzy mathematical programming (FMP) methods were developed to reflect vague information and to deal with uncertainties expressed as fuzzy sets. The conventional fuzzy sets with fixed membership functions may have limitations in practical applications. Since the choice of fuzzy membership functions is highly subjective, they may be also imprecisely stated by decision makers, leading to a second level of fuzziness. Therefore, a concept of interval-valued membership function was proposed to address such complexities which are beyond the capacity of conventional methods (Wang and Huang, 2013).

This study aims to develop an inexact mixed-integer linear programming with interval-valued membership function (IMILP-IMF) approach as well as apply it to power-generation capacity planning under uncertainty. IMILP-IMF incorporates interval-parameter programming (IPP), fuzzy linear programming (FLP), and mixed-integer linear programming (MILP) within a general framework. A concept of interval-valued membership function is introduced to address uncertainties existed in fuzzy goal and fuzzy constraints. A case study will be conducted for demonstrating how the IMILP-IMF approach can facilitate generation capacity planning under uncertainty. Solutions for capacity expansion, air pollution control, and energy resources allocation will be generated. They can help decision makers not only generate alternatives regarding sustainable EPS planning with pollutants control, but also gain insight into the tradeoff among electricity demand, environmental requirement, and economic consideration.

2. Methodology

Fuzzy flexible programming (FFP) can treat decision making problem under fuzzy goal and constraints, where the fuzzy goal and constraints represent the flexibility of the target values in objective function and the elasticity of constraints (Li et al., 2013). A decision in a fuzzy environment can be defined as the intersection of membership functions corresponding to fuzzy objective and constraints (Chang et al., 1997; Huang et al., 2001; Miao et al., 2014). Given a fuzzy goal (G) and a fuzzy constraint (C) in a space of alternatives (X), a fuzzy decision set (D) can then be formed in the intersection of G and C. In a symbolic form,$D = G \cap C$, and correspondingly:

$$\mu_D = \mathrm{Min}\{\mu_G,\ \mu_C\} \tag{1}$$

where μ_D, μ_G and μ_C denote membership functions of fuzzy decision D, fuzzy goal G, and fuzzy constraint C, respectively (Sala, 2008). Letting $\mu_{C_i}(X)$ be membership functions of constraints $C_i(i = 1,2,\ldots,m)$ and $\mu_{G_j}(X)$ be those of goals$G_j(j = 1,2,\ldots,n)$, a decision can then be defined by the following membership function (Li and Huang, 2009):

$$\mu_D(X) = \mu_{C_i}(X)^*\mu_{G_j}(X) \tag{2}$$

where "*" denotes an appropriate and possibly context-dependent "aggregator"; which combines the membership functions of fuzzy goal and fuzzy constraints into a single membership function of fuzzy decision. Then, consider a fuzzy linear programming (FLP) problem:

$$\mathrm{Max}\, f \underset{\sim}{=} CX \tag{3a}$$

subject to:

$$AX \underset{\sim}{\leq} B \tag{3b}$$

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