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Planning renewable energy in electric power system for sustainable development under uncertainty – A case study of Beijing

S. Nie [a], Charley Z. Huang [b], G.H. Huang [c,d], Y.P. Li [c,d,*], J.P. Chen [d], Y.R. Fan [d], G.H. Cheng [d]

[a] Faculty of Applied Science and Engineering, University of Toronto, Toronto, ON M5S 1A4, Canada
[b] Department of Civil Engineering, University of British Columbia, Vancouver, BC V6T 1Z4, Canada
[c] Sino-Canada Resources and Environmental Research Academy, North China Electric Power University, Beijing 102206, China
[d] Institute for Energy, Environment and Sustainable Communities, University of Regina, Regina, Saskatchewan S4S 0A2, Canada

HIGHLIGHTS

- Interval type-2 fuzzy fractional programming is developed to optimize ratio problem.
- It is advantageous in reflecting conflicting objectives and complex uncertainties.
- Uncertainties existed as interval numbers and type-2 fuzzy intervals are quantified.
- Results reveal that share of renewable power generation in gross supply increase.
- Alternative to manage mixed energy system with sustainable development is suggested.

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ABSTRACT

An interval type-2 fuzzy fractional programming (IT2FFP) method is developed for planning the renewable energy in electric power system for supporting sustainable development under uncertainty. IT2FFP can tackle output/input ratio problems where complex uncertainties are expressed as type-2 fuzzy intervals (T2FI) with uncertain membership functions. The IT2FFP method is then applied to planning Beijing electric power system, where issues of renewable energy utilization, electricity supply security, and pollutant/greenhouse gas (GHG) emissions mitigation are incorporated within the modeling formulation. The obtained results suggest that the coal-fired power would continue to decrease and the share of renewable energy in gross electricity supply would maintain an increasing trend. Results also reveal that imported electricity plays a significant role in the city's energy supply. A number of decision alternatives are also analyzed based on the interval solutions as well as the projected applicable conditions, which represent multiple options with sustainable and economic considerations. The optimal alternative that can give rise to the desirable sustainable option under the maximization of the share of renewable power generation has been suggested. The findings can help decision makers identify desired alternatives for managing such a mixed energy system in association with sustainable development. Compared with the conventional optimization methods that optimize single criterion, it is proved that IT2FFP is advantageous in balancing conflicting objectives and reflecting complicated relationships among multiple system factors as well as in tackling various subjective judgments of decision makers with different interests and preferences.

1. Introduction

For decades, fossil fuel consumption as well as its environmental adverse impacts has become a substantial universal concern. More than 80% of worldwide primary energy production comes from combustion of fossil fuel; merely 16% of the global energy consumption is generated by renewable energy sources [1]. For China, with the rapid growth of economy, industrialization and urbanization, its primary energy consumption and electricity demand increased respectively with annually average growth rate of 8.9% and 11.4% during 2000–2012; coal played dominate role in the supply of primary energy and electricity, accounting for 66.6% of the national primary energy consumption in 2012 [2]. The

* Corresponding author at: Sino-Canada Resources and Environmental Research Academy, North China Electric Power University, Beijing 102206, China. Tel.: +86 10 6177 3887; fax: +86 10 6177 3889.
E-mail address: yongping.li@iseis.org (Y.P. Li).

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energy systems worldwide face a rapid transformation from a dominant fossil-fueled towards a low-carbon and clean electricity generation mix. Renewable energy has attracted considerable public attention as environmental pollution and climate change, driven by the excessive utilization of fossil fuels, have deteriorated [3]. For example, the European Union has adopted an explicit target for the share of renewable energy in total consumption/supply since 2009 [4]. Renewable energy technologies are steadily becoming a greater part of the global energy mix, particularly in regions that have put in place policies and measures to promote their utilization [5]. Numerous parameters have to be taken into account in order to identify the optimal power mix for satisfying electricity load, which are related to a number of impact factors of technical (e.g., conversion efficiency, resource availability), economic (e.g., capital cost, fuel cost, operational cost) and political (e.g., power market regulation, emission reduction, industrial barrier). In such an energy mix system, various behaviors, factors, and parameters should be modeled, each of which is associated with uncertainties [6]. These uncertainties can not only create complexities which are beyond the capabilities of deterministic models but also affect the relevant optimization analysis and the corresponded decision making.

Previously, a number of research efforts were conducted on energy systems planning in response to such complexities and uncertainties [7–13]. El-Tamaly and Mohammed [14] determined the impact of interconnecting photovoltaic/wind energy system from reliability point of view using fuzzy logic based reliability index for hybrid electric power systems. Weber and Martinsen [15] proposed a fuzzy linear programming approach to optimize the German energy system for various targets specified by energy indicators of sustainable development, where a crisp equivalent of the fuzzy problem was used for an arbitrary t-norm. Koltsaklis et al. [5] presented an optimization approach to address the generation expansion planning problem of a large-scale, central power system in a highly uncertain and volatile electricity industry environment, where Monte Carlo method was used for capturing the uncertainty in parameters such as fuel price, power unit availability, and electricity import/export. Osório et al. [16] advanced a probabilistic approach to solve the economic dispatch problem with intermittent renewable energy sources, in which the corresponding probability distribution function of available wind power generation was introduced to the optimization problem in order to probabilistically describe the power generation of each thermal unit, wind power curtailment, energy not supplied, excess of power generation, and total generation cost. Şengül et al. [17] developed a fuzzy multi-criteria decision making method for ranking the renewable energy supply systems in Turkey, and results showed that the hydropower is the most suitable renewable energy supply in Turkey. Zhou et al. [18] developed a fuzzy-interval possibilistic programming method for planning sustainable electric power system, which enhanced the traditional fuzzy programming by choosing necessity degree of constraints based on decision maker's preference and avoiding complicated intermediate models with high computational efficiency.

Fuzzy programming (FP) is useful for dealing with vagueness and ambiguity based on fuzzy sets theory, where uncertainties are handled in a direct way without a large number of realizations [19]. However, the conventional FP could merely solve the decision problems containing crisp fuzzy sets [e.g., (b_1, b_0, b_2) with triangular membership function or (b_1, b_2, b_3, b_4) with trapezoidal membership function], whose membership grade [e.g., $u(x)$] is a real number in [0, 1]. In fact, in energy systems planning problems, the membership grades of fuzzy sets are uncertain (i.e. cannot be expressed as precision information), resulting in type-2 fuzzy sets (T2FS). Type-2 fuzzy analysis (T2FA) approach is called for reflecting such T2FS ($\tilde{b}_1$, b_0, $\tilde{b}_2$) whose left and right end points ($\tilde{b}_1$ and $\tilde{b}_2$) are uncertain [20,21]. A few researchers employed the T2FA technique for planning production, transportation as well as fuzzy logic systems to investigate linguistic uncertainties [22–24]. However, few studies of energy systems planning were reported in reflecting such complicated uncertainty (i.e. fuzzy sets with uncertain membership functions).

The conventional optimization methods focused on modeling inputs and outputs neglect of optimizing system efficiency presented as output/input ratios (e.g., renewable power generation vs. system cost). The traditional single-objective programming approaches are normally aimed at identifying the most economic solutions with minimized costs, where environmental impacts are rigidly restricted in the constraints or roughly quantified as costs in the objective function [25]. Fractional programming can tackle ratio optimization problems (i.e. two-objective optimization such as cost/time, output/input, or cost/volume), which can compare objectives of different aspects directly through their original magnitudes and provide an unprejudiced measure of system efficiency [26,27]. Zhu et al. [25] presented an inexact mixed-integer fractional programming approach for supporting sustainable energy system management, which could plan power-generation expansion with the ratio objective function; however, this method could merely reflect uncertainties existed as discrete intervals and was incapable of tackling uncertainties presented as type-2 fuzzy intervals (i.e., $[(\tilde{b}_1^-,\ b_0^-,\ \tilde{b}_2^-),\ (\tilde{b}_1^+,\ b_0^+,\ \tilde{b}_2^+)]$, abbreviated as T2FI). In many real-world problems, results produced by optimization techniques can be rendered highly questionable if the modeling inputs cannot be expressed with precision. It is inevitable that renewable energy sources introduce more variability and uncertainty to the mix system operation owing to their intermittent nature. For example, uncertain electricity demand are estimated as interval values; simultaneously, the lower and upper bounds of these intervals are expressed as T2FS, leading to more complicated uncertainty (i.e. type-2 fuzzy intervals). The inherent complexity and uncertainty that exist in energy mix systems have essentially placed them beyond the conventional optimization methods.

Therefore, the objective of this study is to develop an interval type-2 fuzzy fractional programming (IT2FFP) method to address the above deficiencies. IT2FFP will incorporate techniques of interval-parameter programming (IPP) and type-2 fuzzy analysis (T2FA) within a fractional programming framework, such that uncertainties expressed as type-2 fuzzy intervals (T2FI) with uncertain membership functions can be effectively tackled. IT2FFP can also optimize the system efficiency represented as output/input ratios. A solution algorithm will be proposed to transform fuzzy-interval constraints into deterministic equivalents, based on interactive algorithm and type reduction technique. The IT2FFP model will be formulated for designing renewable energy utilization thereby achieving sustainability for Beijing electric power system. The efficiency of renewable power generation vs. system cost will be optimized, which can help decision makers analyze the alternatives among renewable energy, electricity supply, and system cost under uncertainty.

2. Interval type-2 fuzzy fractional programming method

Fuzzy sets theory, which describes the ambiguity and uncertainty in mathematics, is effective in dealing with to what extent an object belongs to a particular set. When the membership grades of fuzzy sets are hard to be estimated as exact values, it is not reasonable to use an accurate membership function for reflecting such an uncertainty [28]. Type-2 fuzzy sets (T2FS), as extensions of the conventional fuzzy sets, are defined as sets whose membership function is also fuzzy (i.e., membership grade of each element is