Electrical Power and Energy Systems 56 (2014) 19–32

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

A Robust Inexact Joint-optimal α cut Interval Type-2 Fuzzy Boundary Linear Programming (RIJ-IT2FBLP) for energy systems planning under uncertainty

L. Jin [a,b], G.H. Huang [a,b,*], D. Cong [c], Y.R. Fan [b,1]

[a] College of Environmental Science and Engineering, Xiamen University of Technology Xiamen, Xiamen 361024, Fujian Province, China
[b] Faculty of Engineering, University of Regina, Regina, SK S4S 0A2, Canada
[c] MOE Key Laboratory of Regional Energy Systems Optimization, S-C Resource and Environmental Research Academy, North China Electric Power University, Beijing 102206, China

ARTICLE INFO

Article history:
Received 22 June 2013
Received in revised form 3 October 2013
Accepted 22 October 2013

Keywords:
Energy systems planning
Joint-optimal α cut
Interval type-2 fuzzy set
Inexact linear programming
Multiple uncertainties

ABSTRACT

In this study, a new Robust Inexact Joint-optimal α cut Interval Type-2 Fuzzy Boundary Linear Programming (RIJ-IT2FBLP) model is developed for planning of energy systems by integrating both the interval T2 fuzzy sets and the Inexact Linear Programming (ILP) methods. It intends to find an optimal solution for energy systems under such uncertainty expressed as interval fuzzy boundary intervals that exist in the right-hand sides of model constraints. It improves the formal Fuzzy sets Linear Programming (FLP) method by using an optimal analysis in order to obtain an appropriate interpretation of type-2 fuzzy intervals and their solutions. The interval type-2 fuzzy boundary method can provide more accurate judgments to measure the dispersion of fuzzy sets. It also improves the formal interval Two-Step solving Method (TSM) by applying a Robust Two-Step algorithm (RTSM), which allows solutions to avoid absolute violation. Then, the developed model is applied to a case study of long term energy resources planning. Solutions related to interval T2 fuzzy sets linear programming are obtained. These help decision makers handle multiple ambiguity issues existing in energy demand, supply and capacity expansions. The results of the RIJ-IT2FBLP model not only deliver an optimized energy scheme, but also provide a suitable way to balance uncertain cost and profit parameters of an energy supply system. Therefore, the RIJ-IT2FBLP is considered a more practical method for energy management under multiple uncertainties.

1. Introduction

Undoubtedly, increased human activities and complex modern energy systems have been further complicated by the mixed effects of social-economic, policy, institutional and environmental subsystems. Consequentially, energy related activities are highly susceptible to external environmental variations that significantly affect energy system performance, such as the Striker Regulations in environment protection altering energy utilization technology (i.e., encouragement of renewable energy usage and improvement of technology efficiency). Thus, it is rather difficult to quantify the generated impact from interactions among various external and internal factors in the macroscopic energy system, like energy demand, energy security strategy, fuel costs, weather conditions, financial constraints, multiple choices of energy resources, and technological improvement. The fact that both historical records and scientific knowledge of many dynamics are not precisely due to artificial or technical errors, as well as social and natural phenomena forecasted by the existing methods are largely unpredictable and often mispredicted results. The resultant unavailability of information or misinformation will directly produce multiple forms of uncertainty and complexity regarding the appropriate data. Take for instance, the fluctuating weather conditions that can cause the uncertainties existing in the available renewable energy resources (such as solar and wind energy), generation efficiency and other associated parameters in renewable energy generation systems.

Moreover, realistic long-term planning procedures should take into account the uncertainties inherent in future projections and the dynamic characteristics varying with time. Therefore, it becomes necessary to introduce a systematic and consistent method to analyze various sources of uncertainty in the energy management system. This will provide decision makers (DMs) with recommendations for policies that are robust in the face of significant uncertainty about future outcomes and provide suggestions on how to reduce the uncertainty efficiently [1,7,8,9,31,14,17,3,40,19,45,46]. Optimization linear programming models are treated as useful and effective tools that have decidedly attracted social interest for many decades. Previously, numerous energy models had been developed for supporting long

* Corresponding author at: Faculty of Engineering, University of Regina, Regina, SK S4S 0A2, Canada. Tel.: +1 306 337 3298.

E-mail addresses: jinle200@uregina.ca (L. Jin), seabook2000@msn.com (G.H. Huang), dongcong1003@yahoo.cn (D. Cong), yurui.fan@gmail.com (Y.R. Fan).

[1] Tel.: +1 306 337 3298

0142-0615/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ijepes.2013.10.029

term energy management [32,44,2,26,33,22,13,23,7,28,41,43, 47,48]. However, most of those methods fall within the Interval Linear Programming (ILP) method. Few of these methods comprehensively or systematically expound upon the fuzzy uncertainties of energy systems. Such uncertainties have great impact on optimization and decision processes. The Fuzzy Linear Programming (FLP) method is an effective method and was developed based on fuzzy theory and interval methodology. By applying fuzzy sets theory in energy management, the ambiguity and vague information of energy resources have been well quantified. However, this approach may lead to a more tedious calculation process, which either may not be suitable for large scale issues, or may make it difficult to directly communicate with optimization processes [25]. Thus, Interval Linear Programming (ILP) has been introduced in the optimal planning process [15]. It allows uncertainties to communicate with optimal models and can interpret uncertainties easier by using a simpler calculation process. More importantly, it can deal with such data that merely know membership function, very common in engineering planning. However, ILP may not be a feasible solution to the problem when the linear model has a highly uncertain parameter in the right hand side and/or in the left hand side of the equation. Because of this, much formal research incorporate both the FLP and ILP methods to fill the weak side of every approach [36,4,16]. However, these integrating methods are not suitable for a situation in which the interval bounds may have other impacting factors.

For example, when investors consider interest costs, the price of crude oil should be [1000 + 1000 * bank rate, 1200 + 1200 * bank rate] dollar per barrel rather than a crisp interval [1000, 1200] dollars per barrel. However, the bank rate changes all the time, so the bank rate could extended to interval-valued boundaries. Moreover, when people considers the elements in such boundary interval have different memberships for being a bank rate, thus such interval should be fuzzy. Therefore, the Full-Infinite Programming (FIP) method is an attractive algorithm developed to deal with boundary uncertainties [5,35] based on functional intervals. The FIP has advantages that improve upon conventional methods by dealing with boundary uncertainties as functional intervals. These improvements increase the ability of the optimal linear model to accommodate uncertainties by allowing functional intervals to describe the lower and upper boundaries uncertainty. This means that, in a non-deterministic environment, the interval numbers are no longer limited to crisp values. Many studies have applied this method in numerous fields, especially in energy and solid waste management [16,18]. However, the main limitation of this method is that uncertainty in the interval transfer processes may lead to some loss of information. For example, the cost of crude oil may keep increasing or decreasing due to the technology or population factors. Therefore, the previous method is not able to reflect such uncertainties. To avoid such issues, a fuzzy boundary interval model has been developed [34]. This model uses fuzzy sets in an attempt to address the uncertainty problems in previous research. However, use of this method can lead to complex calculations, which are grudgingly accepted by many researchers. To deal with these uncertainties, an interval-valued fuzzy sets model [6] was developed to deal with such uncertainties by using a few α cuts to represent a crisp approximation of fuzzy sets. Although these α-cuts were specially selected, it was not possible to avoid the arbitrariness in some particular cases. These finite α-cuts can potentially ignore some fuzzy information, which might contain essential information. A new infinite α-cuts method [42] was developed to solve this problem. Although this infinite α-cuts method has a complete theory, it only deals with one a special case of fuzzy set bounds, which has a crisp membership function fuzzy sets and cannot represent higher level of fuzzy sets theory. The formal fuzzy sets or type-1 fuzzy sets method assume that the membership function is unknown. Unfortunately, it is no possible, in practice, to determine a crisp membership function for a fuzzy set boundary. Therefore, by using T2 fuzzy sets method, it can provides grades of membership that are also fuzzy, which can describe fuzzy uncertain more complete. Therefore, the type-2 fuzzy set provides grades of membership that also are fuzzy. For example, the price of crude oil is not only influenced by interest rates and population impacts, but also its value which fluctuates throughout the day due to numerous conditions. Consequently, an optimal α-cut, with joints that consider upper and lower bounds of higher level fuzzy sets, should be developed to fully address interval fuzzy set interval bounds. This proposed interval type-2 fuzzy sets boundary method provides several enhancements to strengthen the weaknesses of previous methods. It is a new method to attempt fuzzy-fuzzy theory with inexact planning methods.

Therefore, the purpose of this paper is to use a type-2 fuzzy sets method to develop a Robust Inexact Joint-optimal α cut Interval Type-2 Fuzzy Boundary Linear Programming model (RIJ-IT2FBLP) to describe multiple uncertainties for energy system planning. The development of RIJ-IT2FBLP necessitates tasks involving: (1) integrating interval linear programming and fuzzy linear programming; (2) increasing the fuzziness (T2 fuzzy sets) of previous models; (3) extending the previous method proposed by Figueria in 2008, which means a pre-defusszificaiton algorithm based on an α-cut method is suggested, transferring Type-2(T2) fuzzy uncertainty into an interval valued approach; (4) developing an energy model (RIJ-IT2FBLP) that has a robust solution method, which can promise that the solutions are not out of boundary controlling; and (5) applying RIJ-IT2FBLP to adjust management of energy resources. The solutions of this model can help in three following ways: (a) It makes a more real simulation of energy flows; (b) It can reveal optimal results between energy demand and consumption; and (c) it can guide decisions for capacity expansion and allocations between non-renewable energy and renewable energy.

2. Modeling formulation

2.1. Interval linear programming method

In the real world, uncertainties have existed in energy management systems due to incomplete statistics and different calculation systems, for example, rounding error. If it manages to accumulate sufficiently, it destroy a numerical solution [38]. These uncertainties are also derived from complicated objective circumstances, which includes various changes in time and space. This makes it clear that uncertainties may lead to inaccurate results for management of energy systems. Consequently, it increases probability of decision mistakes. However, the interval method, a qualitative and quantitative measurement for uncertainties, can provide a tightness boundary under such conditions. The Inexact Linear Programming (ILP) [25] can reflect both objective function and constraints uncertainties most effectively as follows:

$$Min\ f^{\pm} = \sum_{j=1}^{n} C^{\pm} X^{\pm} \tag{1a}$$

Subject to

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

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

where $A^{\pm} \in \{R^{\pm}\}^{m\times n}$, $C^{\pm} \in \{R^{\pm}\}^{1\times n}$, $B^{\pm} \in \{R^{\pm}\}^{m\times 1}$, $X^{\pm} \in \{R^{\pm}\}^{n\times 1}$; $R^{\pm}$ denotes a set of interval numbers; $A^{\pm} = \left(a_{ij}^{\pm}\right)_{m\times n}$, $C^{\pm} = (c_1^{\pm}, c_2^{\pm}, \cdots, c_n^{\pm})$, $B^{\pm} = \left(b_1^{\pm}, b_2^{\pm}, \cdots, b_m^{\pm}\right)^T$ and $X^{\pm} = (x_1^{\pm}, x_2^{\pm}, \cdots, x_n^{\pm})^T$. An interval number $(a^{\pm})$ was defined as $a^{\pm} = [a^-, a^+] = \{t \in a | a^- \leqslant t \leqslant a^+\}$ by