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Planning of regional energy systems: An inexact mixed-integer fractional programming model

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HIGHLIGHTS

- An inexact fractional energy system planning (IMIF-EP) model is developed.
- IMIF-EP generates useful results for a case of sustainable energy management (SEM).
- Issues related to sustainability, uncertainties and dynamics can be reflected.
- A comparative case of economical energy management (EEM) is also considered.
- Results of two cases show significant differences between SEM and EEM.

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ABSTRACT

In this study, an inexact mixed-integer fractional energy system planning (IMIF-EP) model is developed for supporting sustainable energy system management under uncertainty. Based on a hybrid of interval-parameter programming (IPP), fractional programming (FP) and mixed integer linear programming (MILP) techniques, IMIF-EP can systematically reflect various complexities in energy management systems. It not only handles imprecise uncertainties and dynamic features associated with power generation expansion planning, but also optimizes the system efficiency represented as output/input ratios. An interactive transform algorithm is proposed to solve the IMIF-EP model. For demonstrating effectiveness of the developed approach, IMIF-EP is applied to support long-term planning for an energy system. The results indicate that interval solutions obtained from IMIF-EP can provide flexible schemes of resource allocations and facility expansions towards sustainable energy management (SEM) under multiple complexities. A comparative economical energy management (EEM) system is also provided. Compared with least-cost models that optimize single criterion, IMIF-EP can better characterize practical energy management problems by optimizing a ratio between criteria of two magnitudes. In application, IMIF-EP is advantageous in balancing conflicting objectives and reflecting complicated relationships among multiple system factors.

1. Introduction

Due to increasing concerns of global environmental change, sustainable energy development has caught world-wide attention [1–4]. However, there are many challenges in the processes of environment-friendly energy systems planning [5]. Firstly, energy system planners are facing difficult decisions in terms of identification for a trade-off between economic development and environmental protection. Secondly, the necessary capacity of energy generation should be determined to meet increasing system demand, which often means that dynamic features of facility capacities need to be reflected and the associated capacity expansion problems should be considered. Thirdly, unforeseen variations exist in system loading, and thus intrinsic uncertainties in some of the key system parameters (e.g. load demands and energy prices) should be properly addressed [6–9]. Therefore, it is desired to develop an integrated model that can systematically reflect complexities related to issues of system sustainability, uncertainty and dynamics in energy management problems.

Previously, many research efforts were made for dealing with the above complexities [10–14]. Among them, optimization methods were widely used to provide sound management schemes under specific system conditions [15–17]. Traditional single-objective programming approaches were normally aimed at

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identifying the most economic solutions with minimized costs, where environmental impacts were rigidly restricted in the constraints or roughly quantified as costs in the objective functions [18,8]. Obviously, the single criterion decision framework of least-cost programming models may lead to unsolvable difficulties in reflecting the system complexities from a sustainable management viewpoint. Since the early 1980s, multi-objective programming (MOP) methods became popular due to the growing socio-environmental awareness and the apparent conflicting nature among economic and environmental concerns [19–27]. For example, Antunes et al. [28] presented a multi-objective model for planning power generation expansion with pollutant emission restrictions. Nasiri and Huang [29] proposed a multi-objective optimization model for large-scale planning of electricity generation. However, the MOP methods usually combined objectives of multiple aspects into a single measure on the basis of subjective assumptions, where identification of weighting factors or economic indicators was considered difficult. Moreover, these methods focused on system inputs and outputs, without optimization for the system efficiency represented as output/input ratios.

Fractional programming (FP) is an effective tool to deal with optimization of ratio, where the objective is quotient of two functions, e.g. cost/time, cost/volume, or output/input [30–34]. It can compare objectives of different aspects directly through their original magnitudes and provide an unprejudiced measure of system efficiency. FP has widely been used in fields of resources management, finance, production and transportation [35,36,31,32,37]. It was indicated that FP could better fit the real problems through considering optimization of ratio between the physical and/or economic quantities. Moreover, FP was proved to be a natural way of approaching both economic and environmental criteria related to the systems' sustainability [38]. Nevertheless, this method has seldom been applied to energy systems planning. One major limitation of applying FP to the energy management systems was that FP problems involving integer variables and uncertain inputs were not effectively handled in the previous studies [39,40].

In fact, expansion of power generation capacity is a crucial issue in a significant number of energy systems planning problems, where integer variables are typically employed to indicate whether a particular facility expansion option is to be undertaken. Mixed integer linear programming (MILP) is thus helpful for tackling such problems of capacity expansion planning [41]. Furthermore, since uncertainties exist in input data and many projection processes, parameters of energy management problems are often difficult to be acquired precisely. In many real-world cases, such inexact parameters can merely be presented as interval numbers with known upper and lower bounds but unknown distribution information. Interval-parameter programming (IPP) is considered as an efficient method to reflect this type of uncertainty [42–44].

For better reflecting the complexities in energy systems, it is desired that an integrated optimization method that can deal with ratio-optimization and capacity-expansion issues be developed. Therefore, the objective of this study is to propose an inexact mixed-integer fractional energy system planning (IMIF-EP) model. Techniques of interval-parameter programming (IPP) and mixed integer linear programming (MILP) will be integrated within a fractional programming (FP) framework. The proposed method can not only tackle ratio optimization problems with imprecise inputs, but also facilitate dynamic analysis of capacity-expansion planning for power generation facilities within a multi-period context. The effectiveness of IMIF-EP method will be demonstrated through a case study of energy system planning, where a number of policy scenarios will be analyzed under varying conditions.

2. Inexact mixed-integer fractional energy system planning model

2.1. Inexact mixed-integer fractional programming

Inexact linear fractional programming (ILFP) is an effective tool to tackle ratio optimization problems under uncertainty, where distribution information is not known exactly, and merely lower and upper bounds are available [45]. In ILFP, interval numbers are used to address imprecise information associated with the related parameters and variables.

Let x denote a closed and bounded set of real numbers. An interval number $x^{\pm}$ is defined as [46]: $x^{\pm} = [x^{-}, x^{+}] = \{t \in x | x^{-} \leqslant t \leqslant x^{+}\}$, where x^{-} and x^{+} are the lower and upper bounds of $x^{\pm}$ respectively. When $x^{-} = x^{+}$, $x^{\pm}$ becomes a deterministic number. Thus, an ILFP problem can be formulated as follows:

$$\text{Max } f^{\pm} = \frac{\sum_{j=1}^{n} c_j^{\pm} x_j^{\pm} + \alpha^{\pm}}{\sum_{j=1}^{n} d_j^{\pm} x_j^{\pm} + \beta^{\pm}} \tag{1a}$$

$$\text{subject to}: \sum_{j=1}^{n} a_{ij}^{\pm} x_j^{\pm} \leqslant b_i^{\pm}, \quad i = 1, 2, \ldots, m \tag{1b}$$

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

where $(x_1^{\pm}, x_2^{\pm}, \ldots, x_n^{\pm})$ is a vector of interval decision variables, $c_j^{\pm}$ and $d_j^{\pm}$ are respectively coefficients in numerator and denominator of the objective, $\alpha^{\pm}$ and $\beta^{\pm}$ are scalar constants, $a_{ij}^{\pm}$ are technical coefficients, and $b_i^{\pm}$ are right-hand-side parameters. Some or all of these parameters can be interval numbers.

In practical planning problems, some of the decision variables are considered as integers. Model (1) can be further improved by incorporating mixed integer programming techniques. Therefore, an inexact mixed-integer fractional programming (IMIFP) model can be developed as:

$$\text{Max } f^{\pm} = \frac{\sum_{j=1}^{t} c_j^{\pm} x_j^{\pm} + \sum_{j=t+1}^{n} c_j^{\pm} y_j^{\pm} + \alpha^{\pm}}{\sum_{j=1}^{t} d_j^{\pm} x_j^{\pm} + \sum_{j=t+1}^{n} d_j^{\pm} y_j^{\pm} + \beta^{\pm}} \tag{2a}$$

$$\text{subject to}: \sum_{j=1}^{t} a_{ij}^{\pm} x_j^{\pm} + \sum_{j=t+1}^{n} a_{ij}^{\pm} y_j^{\pm} \leqslant b_i^{\pm}, \quad i = 1, 2, \ldots, m \tag{2b}$$

$$x_j^{\pm} \geqslant 0, \quad j = 1, 2, \ldots, t \, (t < n) \tag{2c}$$

$$y_j^{\pm} \geqslant 0 \text{ and } y_j^{\pm} \text{ is interval-integer variable}, \quad j = t+1, \ldots, n \tag{2d}$$

where interval-integer variable is defined as: $y_j^{\pm} = \{y_j | y_j^{-} \leqslant y_j \leqslant y_j^{+}$, and y_j^{-}, y_j, y_j^{+} are all integers$\}$. Typically, an interval-binary variable is defined as: $y_j^{\pm} = \{y_j | 0 \leqslant y_j \leqslant 1, \text{ and } y_j = \text{integers}\}$.

It is difficult to tackle such a model with the existing methods. Through applying techniques of interval-parameter programming (IPP), linear fractional programming (LFP), and mixed-integer linear programming (MILP), an interactive transform algorithm is then developed for solving the IMIFP model.

Let $\mathbf{S}$ be the feasible set for Model (2):

$$\mathbf{S} = \left\{ (x_1, \ldots, x_t, y_{t+1}, \ldots, y_n) \middle| \sum_{j=1}^{t} a_{ij}^{\pm} x_j + \sum_{j=t+1}^{n} a_{ij}^{\pm} y_j \leqslant b_i^{\pm}, \quad \forall i; \; y_j = integer, \; j = t+1, \ldots, n; \; x_j, y_j \geqslant 0, \forall j \right\}$$

Assumed that $\sum_{j=1}^{t} d_j^{\pm} x_j^{\pm} + \sum_{j=t+1}^{n} d_j^{\pm} y_j^{\pm} + \beta^{\pm}$ is strictly positive for every $(x_1, \ldots, x_t, y_{t+1}, \ldots, y_n) \in \mathbf{S}$.

For convenience, we assume that objective value $f^{\pm}(x_1, \ldots, x_t, y_{t+1}, \ldots, y_n)$ is also positive for $(x_1, \ldots, x_t, y_{t+1}, \ldots, y_n) \in \mathbf{S}$. According