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A robust flexible-probabilistic programming method for planning municipal energy system with considering peak-electricity price and electric vehicle

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ABSTRACT

Effective electric power systems (EPS) planning with considering electricity price of 24-h time is indispensable in terms of load shifting, pollutant mitigation and energy demand-supply reliability as well as reducing electricity expense of end-users. In this study, a robust flexible probabilistic programming (RFPP) method is developed for planning municipal energy system (MES) with considering peak electricity prices (PEPs) and electric vehicles (EVs), where multiple uncertainties regarded as intervals, probability distributions and flexibilities as well as their combinations can be effectively reflected. The RFPP-MES model is then applied to planning Qingdao's MES, where electrical load of 24-h time is simulated based on Monte Carlo. Results reveal that: (a) different time intervals lead to changes of energy supply patterns, the energy supply patterns would tend to the transition from self-supporting dominated (i.e. in valley hours) to outsourcing-dominated (i.e. in peak hours); (b) 15.9% of total imported electricity expense would be reduced compared to that without considering PEPs; (c) with considering EVs, the CO_2 emissions of Qingdao's transportation could be reduced directly and the reduction rate would be 2.5%. Results can help decision makers improve energy supply patterns, reduce energy system costs and abate pollutant emissions as well as adjust end-users' consumptions.

1. Introduction

Continuing population expansion and economic development resulting in excessive stress on fossil resources (e.g., coal, oil and gas) and increased electricity demand, which has made the electric power systems (EPS) become more fragile as well as overused [1]. Exploring new ways to ameliorate security and efficiency of the EPS with a stable and sustainable method, in terms of research on power planning is of vital significance. Peak electricity prices (PEPs) as one of demand response measures aims at changing end-users' normal consumption patterns in response to the price of time-of-use, or inducing electricity with lower price when the reliability of EPS is jeopardized [2]. Since electricity demand is varied during different periods of a day, PEPs could be useful for load shifting and reducing electricity demand in peak hours. On the other hand, as energy consumers, PEPs can be effective for cutting down the electricity expense, which is of importance to improve the end-users' lives. Therefore, effectively planning EPS in association with considering PEPs of 24-h time is indispensable in terms of load shifting, pollutant mitigation and energy demand-supply reliability as well as reducing electricity expense of end-users [3,4].

Previously, numerous studies were developed for planning energy system with considering PEPs [5–12]. For example, Anbazhagan and Kumarappan [6] used a DCT input featured FFNN model to forecast the day-ahead electricity price in Spain market, results demonstrated that the DCT-FFNN model is effective and less computation time than the recent models. Abedinia et al. [8] proposed a new stochastic search method to predict the future values of electricity prices, results showed that the proposed method could outperform traditional methods. Shayeghi et al. [10] presented a Multi-Input Multi-Output (MIMO) model to establish the correlation between electricity price and load, results indicated that the algorithm can be superior adapted to real market in smart grid environment. Alayo and García [13] presented a static deterministic linear peak-load pricing model for planning the EPS of Peruvian, the evolution of the capacity mix for the years 2008–

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2013 was effectively assessed based on the given duration curve. Kato et al. [14] examined the consumer responses to critical peak pricing, where about [50.4, 60.9] % of total electricity-saving amount was impacted by maximum-saving behavior. Wang and Li [15] analyzed critical peak pricing (CPP) in California for manufacturing applications, in which 30% of electricity savings and 5.63% of GHG emissions reduction were achieved by adopting CPP. Summarily, these studies were mainly focused on statistic deterministic methods to predict future electricity prices, examine the consumer reflections on peak pricing and solve demand-side management problems. For a real-world EPS planning, PEPs would be affected by numbers of factors (e.g., interest and inflation rates, resources availabilities and end-users' consumption responses), which made these deterministic methods become infeasible [16]. Besides, they were incapable of reflecting the complex interaction among various power generation facilities associated with temporal/spatial variations of energy resources and environmental and economic features of individual technology [17].

In the real-world energy systems planning problems, various uncertainties presented as different formats were existed in the planning processes [18–21]. A number of inexact optimization approaches were formulated for handling such complexities and uncertainties in EPS planning [22–27]. For example, Heck et al. [24] used Monte Carlo approach to analyze the potential investments in electricity generation, where uncertainties of levelized electricity cost were solved based on probability distributions. Tan et al. [25] proposed a fuzzy linear programming enterprise input-output model for optimal crisis operations in industrial complexes, in which resource consumption, net final product outflow and production level expressed as fuzzy goals or constraints were handled. Simic [26] developed an interval-parameter two-stage stochastic full-infinite programming approach for end-of-life vehicles allocation management, where uncertainties presented as crisp intervals and probability distributions were tackled. Narayan and Ponnambalam [28] proposed a risk-averse stochastic programming approach for microgrid planning, in which random variables of the capacity of solar power, wind power, diesel generation and storage were tackled. Chen et al. [29] developed a copula-based fuzzy chance-constrained programming model for electric power generation systems planning, where uncertain capacities of solar energy and wind power were handled by the joint probability distribution. Generally, the above methods were effective for handling uncertainties expressed as simplified and static phenomena such as fuzzy constraints, probability distributions, and functional intervals. However, they have difficulties in reflecting uncertainties corresponding to flexible constraints about fixed and variable activity costs. Flexible programming (FP) can handle this problem which is associated with soft constraints and flexibility on target value of goals [30]. Besides, multi-uncertainty can further exist in EPS planning problems in terms of multi-source, multi-user and multi-period context, which could not only affect the planning processes and decision schemes, but also caused many EPS issues beyond the traditional optimization approaches [31].

Therefore, this study aims at developing a robust flexible probabilistic programming (RFPP) method for planning municipal energy system (MES). RFPP will be used for tackling multiple uncertainties expressed as intervals, probability distributions and flexibilities as well as their combinations. Then, a RFPP-MES model will be formulated for planning Qingdao's MES, where Monte Carlo technique will be used for simulating the electrical load of 24-h time under different time intervals (e.g., peak hour, rush hour, flat hour and valley hour). Results will help decision makers to optimize power-supply patterns, protect power demand-supply security and reduce pollutant emissions, as well as motivate consumers to adjust their consumption attitude towards load shifting and reducing peak electricity demand.

2. Methodology

Robust flexible programming (RFP) is effective for handling flexibility on target value of goals and soft constraints employed to the first and third constraints [32]. With regard to the satisfaction degrees on the flexible constraints, a RFP model can be depicted as follows [33,34]:

$$\text{Min } E = cx + fy \tag{1a}$$

subject to:

$$Ax \geqslant d - \tilde{t}(1-\alpha) \tag{1b}$$

$$Bx = 0 \tag{1c}$$

$$Sx \leqslant Ny + [\tilde{r}(1-\beta)]y \tag{1d}$$

$$Ty \leqslant 1 \tag{1e}$$

$$y \in \{0,1\},\ x \geqslant 0 \tag{1f}$$

where vectors x and y are regarded as continuous and binary variables, respectively; vectors f and c are related to fixed opening costs of facilities and variable activity costs, respectively; vector d is representative of customers' demand; matrices A, B, S, T and N represent constraints' coefficients where N is indicator of facilities' capacity.

Parameters α and β are indicator of minimum satisfaction level of flexible constraints. Triangular fuzzy numbers $\tilde{t}$ and $\tilde{r}$ can be represented by three prominent points (i.e. $\tilde{t} = (t^p, t^m, t^o)$ and $\tilde{r} = (r^p, r^m, r^o)$). Based on the fuzzy ranking method suggested by [35,36], $\tilde{t}$ and $\tilde{r}$ can be defuzzified as follows:

$$\left(t^m + \frac{\vartheta_t - \vartheta'_t}{3}\right) \tag{2}$$

$$\left(r^m + \frac{h_r - h'_r}{3}\right) \tag{3}$$

where parameters ϑ_t and ϑ'_t (h_r and h'_r) are lateral margins of the triangular fuzzy number $\tilde{t}(\tilde{r})$ and can be defined as follows:

$$\vartheta_t = t^o - t^m \tag{4}$$

$$\vartheta'_t = t^m - t^p \tag{5}$$

Based on Eqs. (2) and (3), model (1) can be converted into the following equivalent crisp one:

$$\text{Min } E = cx + fy \tag{6a}$$

subject to:

$$Ax \geqslant d - \left(t^m + \frac{\vartheta_t - \vartheta'_t}{3}\right)(1-\alpha) \tag{6b}$$

$$Bx = 0 \tag{6c}$$

$$Sx \leqslant Ny + \left[\left(r^m + \frac{h_r - h'_r}{3}\right)(1-\beta)\right]y \tag{6d}$$

$$Ty \leqslant 1 \tag{6e}$$

$$y \in \{0,1\},\ x \geqslant 0 \tag{6f}$$

Although the RFP model is effective for supporting various fuzzy ranking approaches based on different fuzzy sets in the soft constraints. Besides, various fuzzy solutions can be obtained under different α-cut satisfaction degrees in soft constraints [30]. However, in practical municipal energy system (MES) management prob-