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An interval-possibilistic basic-flexible programming method for air quality management of municipal energy system through introducing electric vehicles

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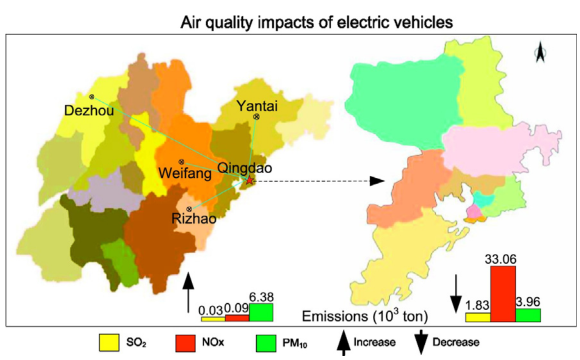
HIGHLIGHTS

- An interval-possibilistic basic-flexible programming (IPBFP) method is proposed.
- It can address dual uncertainties as interval-possibilistic and -flexible variables.
- IPBFP is applied to planning municipal energy system of Qingdao.
- Solutions of various EVs stimulation levels are discussed.
- Results create tradeoff among system cost, pollutant emission and EVs development.

GRAPHICAL ABSTRACT



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ABSTRACT

Contradictions of sustainable transportation development and environmental issues have been aggravated significantly and been one of the major concerns for energy systems planning and management. A heavy emphasis is placed on stimulation of electric vehicles (EVs) to handle these problems associated with various complexities and uncertainties in municipal energy system (MES). In this study, an interval-possibilistic basic-flexible programming (IPBFP) method is proposed for planning MES of Qingdao, where uncertainties expressed as interval-flexible variables and interval-possibilistic parameters can be effectively reflected. Support vector regression (SVR) is used for predicting electricity demand of the city under various scenarios. Solutions of EVs stimulation levels and satisfaction levels in association with flexible constraints and predetermined necessity degrees are analyzed, which can help identify the optimized energy-supply patterns that could plunk for improvement of air quality and hedge against violation of soft constraints. Results disclose that largely developing EVs can help facilitate the city's energy system with an environment-effective way. However, compared to the rapid growth of transportation, the EVs' contribution of improving the city's air quality is limited. It is desired that, to achieve an environmentally sustainable MES, more concerns should be focused on the integration of increasing renewable energy resources, stimulating EVs as well as improving energy transmission, transport and storage.

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1. Introduction

As the primary contributor of economic development and social revolution, automotive industry has facilitated the human race (Casals et al., 2016). Fossil fuel crises and environmental pollution issues (e.g., emissions of sulfur dioxide (SO_2), nitrogen oxide (NO_X) and particulate matter (PM)) due to the rapid growth of transportation continue to be challenges faced by decision makers (Achour and Belloumi, 2016). In China, transportation sector accounts for around 8.4% of energy consumption and the petroleum products bear 57.4% of the total petroleum energy consumption; nevertheless, as the key emitters of GHG, transportation occupies approximately 14.0% of total GHG emissions (Pachauri et al., 2014; National data, 2016). Contradictions of sustainable transportation development and environmental issues have been aggravated significantly and been one of the major concerns for energy systems planning and management. A heavy emphasis is placed on integration of renewable energy resources, stimulation of electric vehicles (EVs), as well as improvement of energy transmission, transport and storage in energy systems to handle these problems (Prebeg et al., 2016; Yu and Stuart, 2017).

Electric vehicles (EVs) represent one of the most promising pathways to increase energy security and reduce emissions of air pollutants (Global EV Outlook, 2013). Overall, EVs and charging infrastructure deployment has continued growing because of the reduction of investment costs, reliability improvement, and efficiency enhancement of EVs. Vehicle electrification has gone multi-model with 46,000 electric buses and 235 million electric two-wheelers deployed; and total EV spending by governments reached 16 billion US$ between 2008 and 2014 (Global EV Outlook, 2016). Although the China's EVs stock accounted for 12.0% of global EVs stock in 2014, the market share merely occupied 0.4%, which was far lag behind than global level (i.e. 3.0%). Utilizing EVs to substitute high pollutant emitters (e.g., private car, bus and truck) becomes important to fulfill sustainable development of energy systems. A municipal energy system (MES) is considerably affected by the integration and stimulation of EVs such as battery storage management, demand forecasting, electricity demand-supply security, as well as other factors (e.g., daily traveled distance, driving habits and road traffic conditions) (Graabak et al., 2016; Soares et al., 2016). For a MES, unique energy, environmental and economic features of individual technology could influence each other, which enforce the MES become more complicated. In responses to such complexities and uncertainties, decisions with sound economic and environmental efficiencies are desired to effectively planning MES (Yu et al., 2016).

Previously, a number of research works were conducted for dealing with uncertainties in the MES (Hajforoosh et al., 2015; Ahmadian et al., 2016; Anand et al., 2016; Brady and O'Mahony, 2016; Falahati et al., 2016; Li et al., 2016; Lin and Chen, 2016; Rabiee et al., 2016; Rathore and Roy, 2016). For example, Hajforoosh et al. (2015) formulated a fuzzy discrete particle swarm optimization method for online PEV charging coordination, in which uncertainties of distribution transformer loading, voltage regulation limits, initial and final battery state of charges were handled. Ahmadian et al. (2016) proposed a probabilistic method for handling uncertainties related to wind distributed generation, load demand as well as plug-in electric vehicles (PEVs). Brady and O'Mahony (2016) used a stochastic simulation methodology to generate a schedule of daily travel and charging profiles for a population of electric vehicles, where uncertainties of the travel and charging behavior of EVs were tackled. Rabiee et al. (2016) developed a two-stage model for dealing with the simultaneous scheduling of electrical vehicles and responsive loads in microgrid, in which uncertainties related to wind and PV were compensated. Generally, the above methods are effective for handling uncertainties expressed as stochastic variables with known probability distributions and fuzzy discrete sets. However, they have difficulties in tackling uncertainties in association with soft constraints and flexibility on target value of goals (e.g., fixed opening costs of facilities and variable activity costs) (Li and Huang, 2009; Elskens et al., 2014; Manaf et al., 2016). In general, flexible programming (FP) deals with soft constraints and flexibility on target value of goals while possibilistic programming is used to cope with imprecise input parameters or the lack of knowledge about the exact value of parameters (Li et al., 2008; Pishvaee and Khalaf, 2016).

Therefore, this study aims at developing an interval-possibilistic basic-flexible programming (IPBFP) method for planning municipal energy system (MES). IPBFP will integrate basic-flexible programming (BFP), interval-parameter programming (IPP) and fuzzy-possibilistic programming (FPP), which can deal with uncertainties presented as interval-flexible variables and interval-possibilistic parameters. The IPBFP method will be applied to planning the MES of Qingdao, where support vector regression (SVR) will be used for predicting electricity demand under various scenarios. Results will help decision makers discern optimal power-generation patterns and reduce air-pollutant emissions through developing EVs.

2. Methodology

Flexible programming (FP) is effective for dealing with soft constraints and flexibility on target value of goals (Li et al., 2009; Pishvaee et al., 2012). Based on the flexibility degrees in the flexible constraints (Bellman and Zadeh, 1970; Mula et al., 2006), a basic-flexible programming (BFP) model can be represented as follows:

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

Subject to:

$$Ax \tilde{\geq} d \tag{1b}$$

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

$$Sx \tilde{\leq} Ny \tag{1d}$$

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

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

where vectors f and c are related to fixed opening costs of facilities and variable activity costs, respectively; vectors x and y are regarded as continuous and binary variables, 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; symbol $\tilde{\geq}$ is regarded as fuzzy version of ≥ which implies that right hand side of constraint is essentially less than or similar to the left hand side value.

Based on Cadenas and Verdegay (1997) and Peidro et al. (2009), two fuzzy numbers ($\tilde{t}$ and $\tilde{r}$) can be used to show the violation of soft constraints. Accordingly, model (1a) can be rewritten as follows:

$$\text{Min } E = cx + fy \tag{2a}$$

Subject to:

$$Ax \geq d - \tilde{t}(1-\alpha) \tag{2b}$$

$$Bx = 0 \tag{2c}$$

$$Sx \leq Ny + [\tilde{r}(1-\beta)]y \tag{2d}$$

$$Ty \leq 1 \tag{2e}$$

$$y \in \{0,\ 1\},\ \ x \geq 0 \tag{2f}$$

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 $\tilde{r} = (r^p,\ r^m,\ r^o)$).