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A flexible-possibilistic stochastic programming method for planning municipal-scale energy system through introducing renewable energies and electric vehicles

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ABSTRACT

Excessive stress on fossil resources has deteriorated energy crisis and environmental problem, such that introducing renewable energies and electric vehicles (EVs) has become a main concern for government. In this study, a flexible-possibilistic stochastic programming (FPSP) method is developed for planning municipal-scale energy system (MES) with cost minimization and emission mitigation. FPSP cannot only deal with multiple uncertainties employed to the soft constraints and objective function, but also analyze the individual and interactive effects of uncertain parameters on system cost. The FPSP method is then applied to planning MES of Beijing under considering the impacts of renewable energies and EVs. Solutions in association with different constraint-violation levels, satisfaction degrees and confidence levels have been obtained. Results disclose that introducing EVs to the study MES can effectively mitigate pollutant emissions, and the emissions of sulphur dioxide (SO_2), nitrogen oxide (NO_x) and inhalable particles (PM_{10}) can be reduced 7.9%, 10.8% and 9.1%, respectively. Results also imply that the city's MES can be adjusted towards a cleaner pattern through developing renewable energies and EVs. Findings can provide support for planning energy system through introducing EVs to high-traffic city and offer scientific information to decision makers for mitigating pollutant emissions under multiple uncertainties.

1. Introduction

1.1. Significance

Traffic problems are raising worldwide concerns in association with fossil energy crisis and environmental pollution (Günther et al., 2015). Beijing (the capital of China), as one of the most high-traffic places around the world, its vehicle ownership has broken 5.6 million. To drive these vehicles, approximately 0.4 billion liter gasoline and 1.1 billion liter diesel are consumed each year, leading to automotive vehicles become the largest emitter of pollutants (e.g., carbon monoxide (CO), hydrocarbon (HC), nitrogen oxide (NOx) and fine particles ($PM_{2.5}$)) (Beijing Statistical Yearbook, 2016). According to Beijing Municipal Environmental Protection Bureau of 2016, about 86% of CO, 32% of HC, 56% of NO_x and 31% of $PM_{2.5}$ were yielded by automotive vehicles. Many national and regional governments have committed to improve the air quality and respond actively through stimulation of renewable energies associated with relevant laws and regulations (Wang et al., 2012; REN21, 2014; Lin and Zhu, 2018). However, air quality improvement is still the most particularly urgent concern for municipal-scale energy system (MES) planning in terms of the growing haze occurrence. Among alternatives to internal combustion engine vehicles, electric vehicles (EVs) are the most mature techniques that are expected to play a significant role in moving towards a sustainable path (Kabatepe and Türkay, 2017). Therefore, there is a need for decision support tools for assisting in the planning of MES through integration of renewable energies and EVs to achieve a sustainable development way (Young and Brans, 2017; Yu et al., 2018a,b).

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1.2. Complexities and uncertainties

A MES is considerably affected by the integration of EVs such as EVs types, battery lives as well as other factors (e.g., daily traveled distance, driving habits and road traffic conditions) (Green et al., 2011; Abu-Madi and Rayyan, 2013; Choma and Ugaya, 2017; Yang et al., 2017; Aliasghari et al., 2018). Besides, in the real-world MES planning problems, uncertainties can exist in both objective function (e.g., imprecise energy purchase cost, fluctuating electricity-generation and capacity-expansion costs) and constraints (e.g., uncertain electricity demands, varied capacities and changed resource availabilities) (Li et al., 2017; Moret et al., 2017). These uncertainties can be brought from not only parameter measurement and its evaluation, but also the cause by all the aspects of energy production, conversion, transportation and utilization (Hemmati et al., 2017; Huang et al., 2017; Suo et al., 2017). Moreover, multiple uncertainties cannot only exist in uncertain constraint (i.e. electricity demand-supply balance constraint) presented as fuzzy sets with probability distributions in the parameter of electricity demand, but also exist in capacity expansion constraints expressed as flexible-possibilistic within one parameter (i.e. expanded capacity for electricity-conversion technology). These complexities and uncertainties have placed the conventional optimization methods in a dilemma obtaining effective strategies for planning the MES problems. Thus, effective systems analysis methods are desired for planning the MES in response to such complexities and uncertainties.

1.3. Research gap

Over the past decades, many inexact optimization approaches (e.g., interval, fuzzy and stochastic programming) were used for planning the MES under uncertainty (Ahmadi et al., 2016; Derghal et al., 2016; Hemmati et al., 2017; Li et al., 2017). Although these methods are effective for tackling uncertainties related to random variables with known probability distribution, interval parameters, and fuzzy sets. However, they are incapable of handling uncertainties employed to the objective function as well as the soft constraints with possibility distributions (Mousazadeh et al., 2015; Yousefi et al., 2017). Moreover, the previous studies have difficulties in dealing with multiple uncertainties (i.e. flexible-possibilistic-stochastic) exited in constraints within one parameter (i.e. electricity demand). Few of studies are employed to identify optimal strategies for planning renewable energies and EVs in a MES involving multiple pollutant emitters, multiple end-users, and multiple EVs types over a multi-period planning horizon.

1.4. Contributions

The major contribution of this study is to develop a flexible-possibilistic stochastic programming (FPSP) method for uncertainty reflection through integrating chance-constrained programming (CCP), flexible programming (FP) and possibilistic programming (PP) into a general framework. Each technique offers a unique contribution towards the enhancement of the FPSP method's capability. Compared to the individual optimization approaches in Ahmadi et al. (2016), Lin and Chen (2016) and Schulze and Mckinnon (2016), FPSP can handle multiple uncertainties expressed as soft constraints and flexibilities, fuzzy possibility distributions and probability distributions as well as their combinations (i.e. flexible-possibilistic-stochastic). In comparison with fuzzy-interval optimization approach proposed by Derghal et al. (2016), FPSP can-not only deal with uncertainties expressed as random variables but also handle uncertainties employed to the soft constraints and flexibilities. Compared to interval-parameter chance-constrained program proposed by Simic and Dabic-Ostojic (2017), FPSP has advantages of reflecting fixed opening costs of facilities and variable activity costs that employed to the soft constraints and flexibilities on target value of goals, especially for the soft constraints with possibility distributions. In comparison with two-stage interval-possibilistic programming approach proposed by Yu et al. (2016) and type-2 fuzzy chance-constrained programming method proposed by Suo et al. (2017), FPSP can effectively deal with soft constraints and flexibilities on target value of goals using fuzzy ranking approaches associated with different fuzzy sets. Summarily, three characteristics of FPSP make it superior to the previous optimization techniques: (a) it can effectively deal with multiple uncertainties presented as flexible-possibilistic-stochastic (integration of flexibility, possibility distribution and probability distribution); (b) it can jointly consider the possible lack of knowledge in data, and possible variability in the target goal and soft constraints; (c) it can be used for quantitatively analyzing the system risk in association with different levels of end-users' electricity demands.

Then, a FPSP-MES model will be formulated for planning the MES of Beijing, in which five end-users' electricity consumptions (i.e. primary industry, industry, construction, residential and tertiary industry) will be examined based on thousand time's Monte Carlo simulations. The objective of FPSP-MES model aims to obtain the minimum system cost in association with series of constraints such as electricity demand-supply balance, capacity expansion, and environmental requirement. Solutions of different probability levels, satisfaction degrees and confidence levels are analyzed to disclose their impacts on modeling outputs. Sensitive analysis will be further undertaken to visualize influence of the factors on the response and to compare the relative magnitude of the effects. Moreover, based on the comparative analyses, the air quality impacts of introducing EVs to the MES, and the accuracy of the results between FPSP-MES model and actual situation will be validated to evaluate the effectiveness of the study system. Results will help decision makers: (a) tackle uncertainties expressed as flexibilities, fuzzy sets and probability distributions, as well as their combinations; (b) discern optimal energy supply patterns in terms of system cost, emission mitigation, energy-supply security, and policy stimulation of renewable energies and EVs; (c) reveal interactions among uncertain optimization techniques as well as their impacts on modeling outputs.

1.5. Objectives

The main objective of this study is to advance such a FPSP method for planning pollutant-emission mitigation with the consideration of renewable energies and EVs. The FPSP-MES model is developed for a complex interrelated network connected by multiple sectors, as shown in Fig. 1. The detailed tasks include: (a) integration of CCP, FP and PP into a general framework to handle flexible, possibilistic and random uncertainties; (b) planning of Beijing MES for demonstrating the efficiency and practicability of the proposed method; (c) analysis of results obtained about electricity generation, capacity expansion, power import and pollutant mitigation as well as system cost; (d) identification of desired strategy among system cost, emission mitigation, and system-failure risk under multiple uncertainties.

2. Literature review

2.1. Impacts of EVs charging

Previously, a number of research works were conducted for exploring the EVs charging impacts on smart grid (SG) such as