Journal of Cleaner Production xxx (2017) 1–15

Contents lists available at ScienceDirect

Journal of Cleaner Production

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

Planning a sustainable urban electric power system with considering effects of new energy resources and clean production levels under uncertainty: A case study of Tianjin, China

Cong Chen [a], Hualou Long [b, c, d, *], Xueting Zeng [e, f]

[a] Donlinks School of Economics and Management, University of Science and Technology Beijing, Beijing, 100083, China
[b] Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing, 100101, China
[c] University of Chinese Academy of Sciences, Beijing, 100049, China
[d] Center for Assessment and Research on Targeted Poverty Alleviation, Chinese Academy of Sciences, Beijing 100101, China
[e] School of Labor Economics, Capital University of Economics and Business, Beijing, 10070, China
[f] Institute for Energy, Environment and Sustainable Communities, University of Regina, Regina, Saskatchewan, S4S 0A2, Canada

ARTICLE INFO

Article history:
Received 19 October 2016
Received in revised form
19 December 2016
Accepted 18 January 2017
Available online xxx

Keywords:
Electric power system
Environment
Clean production
Low carbon
Risk-aversion
Sustainable urban transformation

ABSTRACT

This study develops a risk-aversion optimization model for an urban electric power system (RAOM-UEPS), taking into account stochastic uncertainties. The RAOM-UEPS can manage stochastic uncertainties and capture associated risks from the stochastic information. This enables managers to analyze the trade-off between system cost and system risk in detail. Then, as a case study, the RAOM-UEPS is applied to the planning of an urban electric power system in Tianjin. Here, three scenarios are considered, each with different proportions of new energy resources and clean production levels (i.e., energy conversion efficiencies). This study aims to develop an urban electric power system (UEPS) optimization model that support the city's transformation from a coal-fired dominated to a low-carbon electric power mix, as well as to promote the sustainable development of society as a whole. The proposed model can facilitate a sophisticated system analysis of energy supply, electric power conversion, capacity expansion, and environment management over multiple periods. The results suggest that coal is dominant in Tianjin's electric power system, which was the primary air-pollutants and CO_2 contributor in electric power system. Improving clean production levels and the proportion of new energy resources could effectively save energy resources and mitigate air pollutants and CO_2 emissions. These findings can provide a scientific basis for the sustainable development of regional electric power systems, as well as for transformation from coal-dominated to low-carbon electric power cities.

1. Introduction

In recent decades, the demand for electricity has increased sharply, mainly owing to rapid economic development, continual urban expansion, population growth, and so on. This increase in electricity demand and the current energy structure have resulted in a series of severe problems, including a shortage of fossil energy, environment pollution, and global warming, which seriously impede the sustainable development of society (Modarres and Izadpanahi, 2016; Yu et al., 2016; Carvalho et al., 2016). These problems are particularly prominent in developing countries, and notably in China (Chen et al., 2016a,b). In China, electricity consumption reached 5.63×10^{12} kWh in 2014, with a growth rate of 34.46% over the previous five years. At the same time, the total installed capacity of electricity reached 1.37×10^9 kW in 2014 (Editorial Committee of China Electric Power Yearbook, 2015). Fossil fuel power played a dominate role in the supply of electricity, accounting for 67.4% of the total installed capacity (Editorial Committee of China Electric Power Yearbook, 2015). Fossil fuel power appears to be a major threat to the environment and the stability of the global climate because it is a major contributor of carbon dioxide (CO_2), sulfur oxides (SO_2), nitrogen oxides (NO_X), and particulate matter (PM) emissions. For example, the SO_2 and NOx emissions from fossil fuel power were 6.2×10^6 and 6.2×10^6

* Corresponding author. Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing, 100101, China.
E-mail addresses: chencong@ustb.edu.cn (C. Chen), longhl@igsnrr.ac.cn (H. Long).

http://dx.doi.org/10.1016/j.jclepro.2017.01.098
0959-6526/© 2017 Elsevier Ltd. All rights reserved.

tons, respectively, in 2014. At the same time, coal contributed 31.4% and 29.8%, respectively, to these emissions (China Statistic Bureau, 2015a; Ministry of Environmental Protection of the People's Republic of China, 2014; The Project Team of the China Coal Cap Plan and Policy Research, 2014). Therefore, it is urgent develop new energy resources (e.g., natural gas, wind, solar, biomass, nuclear, waste) to adjust the present energy structure and to mitigate the conflict between economic development and greenhouse gas (GHG) emissions and air-pollutants. However, new energy resources have not been widely adopted because of their higher operation costs and technical level (Chen et al., 2016a,b). Therefore, it is necessary that decision-makers propose strategic and effective methods to plan for UEPS development and to accelerate the transformation of the city's electric power systems from being dominated by coal to using a low carbon power mix (Chen et al., 2012; Zhou et al., 2013; May et al., 2015; Luthra et al., 2015; Raza et al., 2015; Arce et al., 2015; Purwanto et al., 2015; Yu et al., 2016; Zhang et al., 2013a, 2013b).

Many researchers have proposed ways of dealing with the conflicts between the increase in electricity demand and the deterioration of the environment. Cormio et al. (2003) proposed a bottom-up energy system linear optimization model to reduce the environmental impact and economic impact of energy systems, as well as to provide decision support (e.g., energy exploitation, power generation). Dicorato et al. (2008) developed a linear programming model based on the energy flow optimization model (EFOM) to evaluate the contribution of distributed-generation production and energy-efficiency actions, while considering environmental constraints. Muis et al. (2010) presented a mixed-integer linear programming model for the optimal planning of electricity generation schemes to meet the specified CO_2 emission targets for electricity generation in Peninsular Malaysia. Mirzaesmaeeli et al. (2010) developed a multi-period mixed-integer linear programming model for electric system planning to meet CO_2 emission targets. López-Peña et al. (2012) used a policy-oriented model of the entire Spanish energy system to assess the effect of promoting energy efficiency and renewable electricity in Spain. The results revealed that improved energy efficiency could save more than EUR 5 billion per year in terms of reduced CO_2 emissions. Modarres and Izadpanahi (2016) developed an aggregate planning model to consider energy planning, demand, and production capacity simultaneously, with minimized operation costs, energy costs, and carbon emissions.

However, few of these studies consider uncertain information of electric power systems. Such uncertainties complicate the planning of energy systems, taking them beyond the reach of conventional methods (Jin et al., 2015). In fact, a UEPS may be thought of as an interrelated network, connected by various processes involving energy allocation, electric power conversion, air-pollutants mitigation, and so on (Zhou et al., 2013). Moreover, many parameters of the systems can be expressed as uncertainties (Zeng et al., 2016). For example, electricity demand is often expressed as a probability distribution format, which varies over time and with different policies under highly variable conditions. Unfortunately, traditional deterministic linear programming models become infeasible when solving these problems. The complexities and uncertainties challenge managers to propose optimal schemes for UEPS planning.

The stochastic programming method (SPM) has received much attention, because it can effectively tackle uncertainties, expressed as a probability distribution (Bagajewicz and Barbaro, 2003; Floros and Vlachou, 2005; Xu et al., 2009a, 2009b, 2010; Li et al., 2010; Chen et al., 2012; Stephen and Maged, 2013; Zeng et al., 2014, 2015; Jin et al., 2015; Bornapour and Hooshmand, 2015; Zhou et al., 2015). Jin et al. (2015) proposed a pseudo-optimal inexact stochastic approach for energy environment system planning, which they applied to the Xiamen energy system as a case study. Zhou et al. (2015) developed an inexact stochastic programming method to support electric power system planning and carbon emission abatement, considering stochastic uncertainties, which they applied to Shenzhen in China. However, the SPM is not able to consider the variability in recourse values, because it assumes that the decision-maker is risk neutral (Bai et al., 1997; Ahmed and Sahinidis, 1998; Chen et al., 2012). Thus, it may become infeasible when managers are risk averse under highly variable conditions (Chen et al., 2012; Piao et al., 2015, Xu et al., 2009a, 2009b, 2010; Li et al., 2010). In fact, under these conditions, energy and environmental systems are often associated with various system-failure risks, for example energy supply shortages and air-pollutants excessive discharge. This limitation of the SPM can compromise system stability, which means it will not provide reasonable energy and environmental management strategies.

The robust optimization (RO) method is an improved stochastic programming method that can effectively incorporate risk aversion into optimization models (Bai et al., 1997; Ahmed and Sahinidis, 1998; Chen et al., 2012). Furthermore, it can capture the notion of risk from stochastic information and find robust solutions for systems planning works (Mulvey et al., 1995; Ahmed and Sahinidis, 1998; Wallace and Fleten, 2003; Xu et al., 2009a, b; Chen et al., 2012). In RO models, uncertain parameters which derived from noisy, incomplete, or erroneous data are handled as random variables with discrete distributions (Xu et al., 2010; Chen et al., 2013). The RO method penalizes costs that are above the expected values. In addition, RO integrates goal programming formulations with a scenario-based description of problem data, and generates a series of solutions that are progressively less sensitive to realizations of the model data from a scenario set. This makes it especially useful for decision-makers who need to evaluate the trade-off between economic and stability considerations (Mulvey et al., 1995; Xu et al., 2010).

In this study, we focus on Tianjin as a case study. Tianjin is a municipality that falls directly under the central government, and is the economic and industrial center of northern China. Coal-fired power in the city, with its dominant position for electricity generation, occupied up to 88.98% until 2014, which is far higher than the Chinese average level (Editorial Committee of China Electric Power Yearbook, 2015). The rapid increase in electricity demand and the unreasonable electricity power structure have led to a series of environmental problems. Therefore, this study aims to establish pathways towards UEPS optimization models that can support the transformation from a coal-dominated to a low-carbon electric power mix city, as well as promote the sustainable development of society as a whole. As such, this study develops a risk-aversion optimization model for UEPS (RAOM-UEPS) planning. The proposed model incorporates the RO approach within an SPM framework, such that uncertainties expressed as probability distributions can be addressed. The model can be used by managers to analyze the trade-off between system cost and system safety in detail. Three scenarios are considered, each with different proportions of new energy resources and clean production levels (i.e., energy conversion efficiency) in order to analyze the effects of "low carbon" and "clean production" levels on the UEPS and the environment. Sustainable energy and environment development pathways are explored through the RAOM-UEPS model. Specifically, the RAOM-UEPS can: (1) effectively tackle uncertainties expressed stochastically and capture the notion of risk from the stochastic information, (2) generate optimization schemes for energy supply, electricity generation, and capacity expansion, and (3) realize reduction pathways in air-pollutants and CO_2 emissions in Tianjin with cost-effective and sustainable ways.