Energy Economics 60 (2016) 357–376

Contents lists available at ScienceDirect

Energy Economics

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

Bayesian interval robust optimization for sustainable energy system planning in Qiqihar City, China

Cong Dong [a], Guohe Huang [a,b,*], Yanpeng Cai [c,d,**], Guanhui Cheng [b], Qian Tan [e]

[a] Institute for Energy, Environment and Sustainable Communities, University of Regina, Regina, Saskatchewan S4S 7H9, Canada
[b] Faculty of Engineering and Applied Science, University of Regina, Regina, Saskatchewan S4S 0A2, Canada
[c] State Key Laboratory of Water Environment Simulation, School of Environment, Beijing Normal University, Beijing 100875, China
[d] Beijing Engineering Research Center for Watershed Environmental Restoration & Integrated Ecological Regulation, School of Environment, Beijing Normal University, Beijing 100875, China
[e] College of Water Resources & Civil Engineering, China Agricultural University, Beijing 100083, China

ARTICLE INFO

Article history:
Received 5 April 2016
Received in revised form 13 October 2016
Accepted 19 October 2016
Available online 31 October 2016

JEL classification:
Q01
Q40
Q41
Q48
Q49
Q52

Keywords:
Qiqihar energy system
Emissions controlling
Robust optimization
Bayesian forecasting
Decision making
Multiple uncertainties

ABSTRACT

Old industrial bases in Northeastern China have been experiencing a series of problems such as energy scarcity, economic slack and environmental pollution due to lack of scientific planning of energy systems. Effective energy system management is desirable for avoiding occurrence of these problems in the following decades under the national policy of revitalizing these industrial bases. This task is challenged by system complexity, data unavailability, and inaccurate demand forecasting which can hardly be resolved in existing studies. For improving energy system management in Qiqihar City, a representative industrial base in Northeastern China, under these challenges, a large-scale and fine-resolution Bayesian interval robust energy system optimization (BIRESO) approach is developed in this study. In detail, the structure, characteristics, problems and complexities of the energy system in this city are identified and analyzed. Based on these efforts, a series of optimized energy system management schemes are generated through construction of a BIRESO model and development of a solution algorithm. The obtained solutions can be ensured to remain robust when input data changes through controlling the degree of solution conservatism in accordance with probabilistic bounds on constraint violation. Furthermore, Bayesian estimation method was employed for effectively achieving dynamic forecast of energy demands. The tradeoff among energy security, economic development and environmental conservation under multiple uncertainties is revealed, and the optimal balance among them is identified. A scenario analysis approach is used to quantify the effects of economic growth on energy system schemes based on several developed scenarios. Results show that the BIRESO approach is capable of providing scientific support for energy supply planning, renewable energy development, technological advancement, facility expansion, energy allocation, pollution control, economic impacts assessment, and other energy related activities in Qiqihar City.

1. Introduction

Currently, over 50% of the world's population lives in cities. This number is expecting to rise to 70% by 2050. Also, a growing concern over sufficiency of energy resources and quality of physical environment has been witnessed in many cities. Such a concern stems from the unrelenting growth of energy use and the associated adverse environmental effects. For example, China is right in the rapid process of industrialization. Urbanization and economic growth in the country will probably keep at high speed for at least twenty years. At the same time, cities are centers of large quantities of population and energy consumptions. According to a report by Dhakal in 2009, the thirty-five largest cities in China consumed over 40% of the country's energy consumption and were correspondingly responsible for the major part of its carbon dioxide emission (Hu et al., 2011). Among them, Qiqihar is one of the most important industrial bases in China. With the strategy of revitalizing the old industrial bases, Qiqihar city is significantly accelerating the development pace of industries, and its economy and society have improved rapidly. All of these advances definitely consume a large amount of energy resources and relay on the development of its energy industry. For meeting energy demands, controlling air pollution, reducing energy related costs, and managing energy facilities, decision makers in cities like Qiqihar are facing many challenges due to the complexities of the energy systems. Thus, it is desired to develop an energy system planning model based on explicit and systematic considerations of environmental protection and economic development in large-scale

* Correspondence to: G. Huang, Faculty of Engineering and Applied Science, University of Regina, Regina, Saskatchewan S4S 0A2, Canada.
** Correspondence to: Y. Cai, School of Environment, Beijing Normal University, Beijing 100875, China.
E-mail addresses: gordon.huang@uregina.ca (G. Huang), yanpeng.cai@bnu.edu.cn (Y. Cai).

http://dx.doi.org/10.1016/j.eneco.2016.10.012
0140-9883/

industrial cities like Qiqihar city (Kambo and Handa, 1991; Connolly et al., 2010; Keirstead et al., 2012).

In the past decades, great research efforts have been carried out to reveal how energy related activities and their economic and environmental implications be wisely planned in urban regions worldwide over medium and long periods (Kambo and Handa, 1991; Groscurth et al., 1995; Sundberg and Karlsson, 2000; Borges and Antunes, 2003; Nilsson and Mårtensson, 2003; Rolfsman, 2004; Sugihara et al., 2004; Pelet et al., 2005; Söderman and Pettersson, 2006; Ahlroth and Höjer, 2007; Jones et al., 2007; Dicorato et al., 2008; Lozano et al., 2009; Barker et al., 2010; Connolly et al., 2010; Ren and Gao, 2010; Keirstead et al., 2012; Al-Mayyahi et al., 2013; Cheng et al., 2016a, 2016b). For example, Kambo and Handa (1991) conducted an analysis of energy and pollution problems that were interconnected with economic structures for addressing regional energy policy issues in the city of Delhi (India).Groscurth et al. (1995) described municipal energy systems in terms of data-flow networks by usinga Network Model of Energy-Services Supply. Sundberg and Karlsson (2000) analyzed how the selected economic and technical factors affect the profitability of an investment in a Swedish city. Borges and Antunes (2003) utilized an input–output energy–economy planning model to clarify the interactions between energy and economic systems. Rolfsman (2004) built the energy system in the city of Linköping in Sweden by proposing an energy system model. Sugihara et al. (2004) determined the urban energy system in Osaka city based on a multi-objective optimization model, considering various energy system alternatives and CO_2 emissions. Pelet et al. (2005) illustrated a holistic method to rationalize the design of integrated energy systems at a municipal scale. Ahlroth and Höjer (2007) analyzed issues of energy prices in a long-term ecologically sustainable society based on comparisons between various economic and sustainability scenarios in several Swedish cities. Dicorato et al. (2008) evaluated the contribution of distributed-generation production and energy-efficiency actions based on an energy flow optimization model. Barker et al. (2010) assessed the effects of climate change for the decarburization of the economy in a Mexican city, by applying an Energy–Environment–Economy model and an atmospheric chemistry model. Connolly et al. (2010) developed a model of Irish energy-system using Energy PLAN in Ireland.

At the same time, given that multiple forms of complexities exist in practical energy systems, it is rather significant to plan energy related activities with the full consideration of system uncertainties (Dhar, 1979; Teghem et al., 1986; Bopp, 1996; Fleten et al., 2007; Kahraman et al., 2009; Liu et al., 2009; Fuss and Szolgayová, 2010; Cai et al., 2009, 2011a, 2011b; Carpaneto et al., 2011a, 2011b; Zangeneh et al., 2011; Chen and Fan, 2012; Choi et al., 2012; Ganguly et al., 2013; Cheng et al., 2008, 2015a,b,in press). For instance, Dhar (1979) introduced fuzzy sets into the long range objectives and constraints of a long-range power system decision model. Kahraman et al. (2009) identified effective renewable energy alternatives for Turkey based on analytic hierarchy process and axiomatic design principles under fuzziness by using fuzzy multicriteria decision-making methodologies. Liu et al. (2009) planned coupled coal and power management systems in north China based on an inexact coupled coal and power management model. Cai et al. (2011a, 2011b) developed a large-scale integrated modeling system for supporting climate change impact analysis and adaptation planning of the province of Manitoba under multi-level uncertainties. Carpaneto et al. (2011a, 2011b) formulated a comprehensive approach based on multiple (i.e., long-, medium-, and short-term) time frames through using electricity price correlated random variables, a Monte Carlo simulation, and multi-year scenarios analysis methods. Zangeneh et al. (2011) determined the optimal size, the ideal location, as well as the proper technology of distributed generation units in distribution systems through a static fuzzy multiobjective model. Chen and Fan (2012) established a mixed integer stochastic programming model to support strategic planning of bioenergy supply chain systems and optimal feedstock resource allocation in California in an uncertain decision environment. Choi et al. (2012) described energy resource allocation under uncertainty and derived an optimal policy for long-term investments in novel energy technologies based on a stochastic dynamic model. Ganguly et al. (2013) presented a novel dynamic programming approach for multi-objective planning of electrical distribution systems.

Comparatively in China, many cities are facing conflicts among economic development, energy security, and environmental protection over the past decades. Effective modeling tools are thus crucial for supporting sustainable development of cities in China. Many planning efforts have been undertaken in China in the past decades (Sadownik and Jaccard, 2001; Lin et al., 2010; Liang and Zhang, 2011; Ma et al., 2011; Feng and Zhang, 2012; Yu et al., 2012; Han et al., 2013; Zhang et al., 2014; Cheng et al., in press). For example, Sadownik and Jaccard (2001) explored community energy management in a Chinese city through the adoption of a spreadsheet model to analyze both the long-term energy demands and the energy supplies. Lin et al. (2010) developed a long-range energy alternatives planning (LEAP) model to assess the effectiveness of urban energy conservation and GHG mitigation measures in Xiamen, a coastal city in China. Liang and Zhang (2011) managed the energy system in Suzhou, a city in Zhejiang province, China through an energy input–output model with carbon emission pinch analysis. Ma et al. (2011) proposed an integrated energy strategy based on a conceptual system model to address energy challenges and dilemma in urban communities in China. Feng and Zhang (2012) analyzed effects of different development alternatives on future energy consumption and carbon emission in Beijing by using LEAP. Yu et al. (2012) utilized an improved two-step floating catchment area method to reflect internal heterogeneity in energy demand and supply and address their interactions in Yong ding County, China. Han et al. (2013) assisted policymakers and planners in identifying optimum decisions regarding energy consumption and carbon emission in an eco-community in China based on a multi-objective prediction and optimization tool. Zhang et al. (2014) used fuzzy integral method for evaluating sustainable energy plans of Nanjing city in China.

However, there were few researches on planning energy management system in large-scale industrial cities within a large industrialized area, such as Qiqihar city in northeast China. As one of the most important industrial bases in China, Qiqihar city has been vigorously developing industry and modern agriculture, which require abundant energy resources supplies. In the context of the intimate association between economy, environment, and energy in Qiqihar, various energy-related decisions need to be evaluated for meeting increasing energy demands and reducing the associated pollution emissions. However, few such researches were systematically conducted for planning the energy systems of old northeast industry bases in China. Also, most of the studies did not effectively consider complex relationships existing in urban energy systems, especially large-scale industrial energy system. Actually, the energy utilization in industrial cities is closely linked to many physical and socio-economic factors, such as geographic and climate conditions, human beings, urban economy, industrial structure, policy or regulation, eco-environment, etc. Thus, the urban industrial energy system is not a single and closed system but a complex giant one. The interactions among these factors may further complicate the system analysis and modeling processes, which may generate multiple forms of uncertainties.

In this paper, aiming at resolving these problems, the Qiqihar energy system model will be developed based on the comprehensive system analysis under the multi-uncertainty context, through adopting the developed Bayesian interval robust energy system optimization (BIRESO) method. Such a developed method could ensure that the solutions remain feasible and near optimal when input data changes through controlling the degree of solution conservatism in accordance with probabilistic bounds on constraint violation. Besides, given uncertainty, feasibility tolerance (allowing a small amount of infeasibility in the uncertain inequality), and reliability levels (representing the violation probability of constraint) will be introduced into this method (Bertsimas and Sim, 2003, 2004). In addition, the second significant problem in energy planning systems is the estimation of energy