Energy 131 (2017) 125–136

Contents lists available at ScienceDirect

Energy

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

Explicit cost-risk tradeoff for renewable portfolio standard constrained regional power system expansion: A case study of Guangdong Province, China

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ARTICLE INFO

Article history:
Received 10 December 2016
Received in revised form
3 April 2017
Accepted 3 May 2017

Keywords:
Renewable portfolio standards
Interval two-stage programming
Risk preference
Risk explicit
Generation expansion planning

ABSTRACT

In this paper, a risk explicit interval two-stage programming (REITSP) model was proposed for supporting the regional electricity generation expansion with renewable portfolio standard (RPS) constraint. It could effectively tackle multiple uncertainties expressed as interval numbers. But unlike the traditional interval two-stage programming model, the proposed REITSP model could provide an explicit trade-off information between system cost and risk for decision makers with different risk preferences. It could minimize the total system cost, as well as the decision risk according to the aspiration risk level of decision maker. The developed REITSP model was applied to the case study in Guangdong Province, China for its long-term electricity system planning. Crisp solutions under different aspiration risk levels for varying RPS targets were obtained and analyzed. The results showed that according to the current available renewable energy and affordable construction speed, the maximum RPS target for Guangzhou Province during 2016–2025 should be 17%. Higher RPS level would promote the renewable energy generation, especially solar power; meanwhile, it would reduce the CO_2 emission and the imported electricity, but with greater investment cost. The obtained results and trade-off information would be valuable for the optimal long-term electricity system expansion planning when facing future uncertain situation.

1. Introduction

Electricity power industry is one of the main contributors of greenhouse gas emission in many countries, and serious environment issues caused by fossil-based electricity generation have raised global concern [1,2]. So far, great efforts for electricity system structure adjustment and control have been made in order to mitigate its adverse effects. Among various measures, renewable energy is regarded as environmental friendly alternative resource to reduce the carbon emission of traditional power industry. Therefore, renewable portfolio standard (RPS), which requires a certain percentage for renewable energy generation, is a popular mandatory policy to promote greater use of renewable energy sources [3]. So far, many countries have implemented RPS at different degree to achieve their ambitious emission reduction goal. For example, in Europe, France, Germany and Britain have set the share of renewable energy in total energy consumption as 23%, 18% and 15%, respectively. In the United States, RPS program has been put forward at state level, for instance, the RPS level of California is 33% [4]. China has also declared to raise its renewable energy share

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http://dx.doi.org/10.1016/j.energy.2017.05.017
0360-5442/

to 20% by 2030 [5]. However, implementing such mandatory policy inevitably leads to great impacts on regional power system design and operation management. Thus, how to make a well-balanced compromise among competing power supply-security, maximum renewable energy accommodation, economic, and environmental objectives in generation expansion planning (GEP) under the regulation of environmental policy has been a major issue to be addressed in recent decades.

Extensive researches on GEP problems have been carried out to search the optimal selection of technology, location, size, and operation mode with a broad range of objectives, such as maximization of project lifetime economic return, minimization of CO_2 emission, minimization of total cost [6,7]. Numerous techniques, such as dynamic programming [8], linear programming [9], nonlinear programming [10], mixed integer programming [11], and evolutionary programming [12,13], have been applied to solve the problem. For example, Koltsaklis and Georgiadis [14] presented a generic mixed integer linear programming (MILP) model for long-term GEP with the consideration of both typical daily constraints and representative yearly constraints. From a policymaker's perspective, Siddiqui et al. [15] formulated a bi-level model to investigate how RPS policy may be designed with the consideration of the energy sector's equilibrium and market structure. In these deterministic models, the accurate estimation of technical parameters and load demand has great impact on the reliability of optimal strategies.

In practice, the uncertain characteristic for regional energy system, such as the stochastic renewable energy penetration, the fluctuant fuel price, and uncertain policy regulation, is inevitable to take into account under the long-term electricity expansion planning [16]. A number of inexact optimization methods, such as fuzzy mathematical programming, stochastic mathematical programming, and interval parameter programming, have been developed to address the uncertain information. Different technologies have their unique advantages in handling the uncertainties. For instance, in the framework of fuzzy mathematical programming, fuzzy membership function is used to reflect the uncertain coefficients in the objective function and constrains, as well as the satisfying attitude of decision maker in multi-objective programming [17,18]. In scenario-based stochastic programming, based on the accurate probability distribution information of uncertain parameters, a large number of scenarios are generated by Monte Carlo simulation or other sampling approaches to formulate the uncertainties [19–21]. Repeated random samplings and computations require a lot of time and effort [22]. In addition, with more uncertainties considered in the model, the number of scenarios would grow exponentially. For instance, Koltsaklis et al. [23] presents a multi-regional, multi-period MILP model with the combination of Monte Carlo simulation for the GEP of a large-scale central power system in a highly uncertain and volatile electricity industry environment. Li et al. [24] addressed the climate change impact on GEP problem by setting discrete climate scenarios to model the uncertainty.

Compared with other fuzzy and stochastic mathematical programming, interval parameter programming (IPP) requires less information, and its solution processes are easy and less computational [25,26]. Due to its merits, many inexact optimization methods are integrated with interval parameter programming for reflecting various uncertain information, and the hybrid models have been obtained a wide application in generation expansion and operation dispatch of electricity system under uncertainty. For example, Ji et al. [27] presented an inexact risk-aversion optimization model for regional electricity system planning with the regard of CO_2 emission cap and trade scheme, and decision maker's risk preference. Under the framework of interval programming, Liu et al. [28] proposed an inexact two-stage chance-constrained programming model for the long-term management of coal and power in north China. Jin et al. [29] developed an inexact mixed-integer linear programming for generation capacity planning, where the uncertainties are expressed by fuzzy sets with interval-valued membership function. In addition, since the mid-long term planning horizon of electricity generation expansion usually covers 5 or 10 years. It is difficult to estimate the accurate probability distribution function of the macro social or economic parameters based on limited history data. Therefore, IPP method is more appropriate for the regional GEP problem in practice.

However, bounded interval value also brings two serious limitations in real world decision making process [30]. The first thing is that the optimal solutions gained from IPP may lead to non-optimal and infeasible optimization schemes. Besides, it cannot provide the trade-off between system profit and risk representing the decision maker's risk attitude. Risk explicit interval linear programming (REILP) approach proposed by Zou et al. [31] can overcome the above shortcomings of IPP solutions. Its effectiveness and capability have been verified in several fields of study. Under the framework of REILP, Liu et al. [32] and Zhang et al. [33] proposed REILP models for water quality management problems. Simic et al. [34,35] developed a REILP model for the end-of-life vehicle recycling in EU under uncertainty, then proposed a refined REILP model by introducing fuzzy set to reflect the decision maker's preferences. In spite of this, only few researches about REILP approach have been carried out, especially in GEP problems.

Hence, in this paper, under the framework of REILP approach, we propose a risk explicit inexact two-stage stochastic programming (REITSP) model to deal with the long-term GEP problems under uncertainties. The main contributions of this work are summarized as: (1) The optimal investment and operation strategies of mid-long term electricity system under different RPS levels is analyzed and compared at regional level; (2) Multiple uncertainties are considered to make the model more practical, but with less required information and computational complexity, which is more executable in real world decision process; (3) Unlike the traditional interval two-stage stochastic programming model, explicit solution with better system cost-risk tradeoff information could be provided according to the risk preference of decision maker.

The remainder of this paper is arranged as follows. The proposed REITSP model programming model and its solution process are presented in Section 2. Detail case study for Guangzhou Province is carried out in Section 3. Sector 4 illustrates the optimal strategies under different RPS levels and compares the optimal solutions of REITSP model with ITSP model. Sector 5 outlines the main conclusions.

2. Methodologies

2.1. Inexact two-stage stochastic programming approach

In the inexact two-stage stochastic programming (ITSP) approach, the parameters in objective function and constraints can be expressed as intervals with lower and upper bound, besides, the stochastic of future events can described by probability distribution function. Thus, ITSP could deal with mixed uncertain information effectively. A key feature of ITSP is the two-stage decision process, where in its first stage, the initial decision is made before the random events occur, and in the second stage, corrective actions can be taken after a random event has taken place, which aims to minimize the "extra penalties" due to recourse against any infeasibility [36]. The mathematical formulation of a typical cost minimization ITSP model is presented as the follows [37,38]: