Renewable Energy 123 (2018) 549–562

Contents lists available at ScienceDirect

Renewable Energy

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

GHG-mitigation oriented and coal-consumption constrained inexact robust model for regional energy structure adjustment – A case study for Jiangsu Province, China

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A R T I C L E I N F O

Article history:
Received 26 September 2016
Received in revised form
20 December 2017
Accepted 11 February 2018
Available online 13 February 2018

Keywords:
Coal consumption cap
Electricity generation expansion
Uncertainty
Robust optimization
Interval two-stage stochastic programming

A B S T R A C T

Resources and environmental crises are involved in energy management system, confronting a larger amount of coal consumption and GHG emission during structure adjustment plan making in China. In this study, a GHG-mitigation oriented and coal-consumption constrained inexact robust energy system management model is developed for adjusting regional power structure and analyzing the effects of different policy instruments on the performance of power system. The proposed model is a hybrid methodology of interval two-stage stochastic programming and stochastic robust programming. It can handle uncertainties presented as discrete intervals and probability distributions, and reflect the tradeoff between system costs and the tractability under different policy scenarios. The proposed model was applied to a case study of Jiangsu Province, a developed region within the total coal consumption control pilot area of China. The results revealed that ambitious carbon emission and coal consumption reduction targets would promote the utilization and development of renewable energy. Stricter carbon emission caps were shown to be more efficient than coal consumption cap policies for encouraging investment in renewable energy generation, especially wind power. If over 15% carbon emission reduction target was carried out, the recent coal consumption control policy would have little impact on the electricity system development.

1. Introduction

Unreasonable energy structure and resource-intensive mode for economic growth has led to excessive consumption of traditional fossil fuels, increasing pressure on environment, and unsustainable development. For example, in China, the coal consumption for power generation industry has reached 1.95 billion tones during 2013, which accounts for 45.98% of the total coal consumption [1]. Meanwhile, greenhouse gases emission associated with the coal consumption has caused a series of serious problems on environmental security and human health. Many policies and regulatory measures have been proposed for adjusting energy system structure, and improving regional environmental quality, such as the coal total consumption control pilot project, and greenhouse gases emission reduction policy in China. CO_2 emissions limit, cap and trade systems, and emissions penalties have gained increasing attention in relation to power generation expansion planning [2]. Based on the previous researches analysis, few studies have considered the effect of coal consumption control policy on power generation expansion planning practices in China [3]. Moreover, there are various uncertain factors associated with economic and technique parameters as well as carbon-emission related to different policies. Such uncertainties would affect the regional electric power generation schedule, and the effect of different control measures on energy structure adjustment. Therefore, faced with global warming, regional environmental pollution, and resources shortage, a GHG-mitigation oriented and coal-consumption constrained regional electric power system

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https://doi.org/10.1016/j.renene.2018.02.059
0960-1481/

management model is desired for sustainable generation expansion planning under various uncertainties.

Previously, in order to reflect the complexities information and deal with the uncertainties in energy system with different multiple temporal and spatial scales, fuzzy mathematical programming, stochastic mathematical programming, and interval-parameter programming, have been developed to handle the uncertainties in energy system planning and management [4–6]. In many real-world problems, several types of uncertainties may exist together in a complex system. As a result, hybrid inexact optimization methods have been proposed and regarded as an efficient tool for uncertain programming. Especially, interval two-stage stochastic programming (ITSP), which can address the probability density and discrete interval uncertainties, has been widely applied in complex energy system [7]. For example, Cai et al. [8] proposed a fuzzy-random interval programming model for identifying optimal strategies in the planning of energy management systems. Ji et al. [9] developed a hybrid inexact stochastic-fuzzy chance constrained programming for regional micro-grid system management. Tan et al. [10] used two-stage programming to solve schedule optimization issues associated with wind power and energy storage devices. Li et al. [11] proposed an interval-fuzzy two-stage stochastic programming model for CO_2 emission trading planning of industry systems under uncertainty. Liu et al. [12] developed a hybrid method by integrating ITSP with chance-constrained programming for the planning of coupled coal and power management systems under China's special coal-pricing mechanism.

In ITSP method, the uncertain variables are expressed as interval values and discrete probability instead of generating a large number of scenarios with Monte Carlo simulations, and it also has the ability to take corrective actions after random events taking place in future. However, the method may be possible to identify a decision policy that is relatively stable with respect to scenarios, especially when the scenarios do not differ drastically from one another. In order to break this limitation and extend the application range in large scale energy system management, robust optimization models offer an alternative to stochastic mathematical programming methods and better applicability to real-life systems [13–15]. The robust optimal strategy is capable of meeting load growths under various uncertainties and is generally more conservative than stochastic programming. The conservative solutions can be controlled by the degree of robustness according to the risk preference of decision makers. For example, Dehghan et al. [16] proposed a tri-level reliability-constrained robust power system expansion planning which accounted for multi-fold uncertainties, such as electricity demand, wind power generation, and availability of units and lines. Wang et al. [17] formulated a two-stage adjustable robust programming model to manage a building energy system with solar power generation. Taking account of the stochastic behaviors of the solar and wind power output and also load demand, Billionnet et al. [18] developed a two-stage robust approach to determine the optimal design of a hybrid energy stand-alone system. Chen et al. [19] proposed a distributionally robust hydro-thermal-wind economic dispatch method to enhance the flexibility and reliability of power system operation.

Therefore, in order to deal with the pressures of energy conservation and carbon emission, the objective of this study is to develop GHG-mitigation oriented and coal-consumption constrained inexact robust model for regional energy system management based on the inexact two-stage stochastic robust programming that integrated by inexact two-stage stochastic programming and robust optimization method for solving a long-term, low-carbon generation expansion planning problem under different regulation policies, and investigating how carbon emission caps and coal consumption control policies may influence future power generation planning. Solutions to the optimization model reflect the trade-off between system cost and low-carbon environmental efficiency. Then, the proposed model was applied to a case study of Jiangsu Province, a developed region of China. To the best of the authors' knowledge, this is the first study to compare the impacts of carbon emission caps and coal consumption control policies on the investment portfolio and performance of electric power system.

The remainder of this paper is organized as following. The relative methodology is introduced in Sector 2. A detail case study of generation expansion planning for Jiangsu Province is analyzed in Sector 3. Results and discussion are presented in Sector 4. Finally, main conclusions derived from the key findings of this study are drawn in Sector 5.

2. Methodology

Interval two-stage stochastic programming is an inexact programming method with the integration of interval parameter programming and two-stage programming. It can handle uncertainties with only minimum and maximum values and uncertainties with probability distribution information simultaneously. The obvious advantage of ITSP is its two-stage decision process, where the first stage decision is undertaken before the realizations of random variables are known, and the second stage decision is made when uncertain events occur. Due to these advantages, ITSP is a popular tool for inexact programing under uncertain scenarios. A typical ITSP model with minimum objective function can be formulated as [20,21]:

$$\min f^{\pm} = \sum_{j=1}^{n_1} c_j^{\pm} x_j^{\pm} + \sum_{j=1}^{n_1} \sum_{s=1}^{N} p_s d_j^{\pm} y_{js}^{\pm} \tag{1a}$$

s.t.

$$\sum_{j=1}^{n_1} a_{rj}^{\pm} x_j^{\pm} \le b_r^{\pm}, r = 1, 2, ..., m_1 \tag{1b}$$

$$\sum_{j=1}^{n_1} a_{ij}^{\pm} x_j^{\pm} + \sum_{j=1}^{n_1} e_{ij}^{\pm} y_{js}^{\pm} \le \widehat{w}_{is}^{\pm}, i = 1, 2, ..., m_2; s = 1, 2, ..., N \tag{1c}$$

$$x_j^{\pm} \ge 0, j = 1, 2, ..., n_1 \tag{1d}$$

$$y_{js}^{\pm} \ge 0, j = 1, 2, ..., n_1; s = 1, 2, ..., N \tag{1e}$$

where the superscript $\pm$ denotes the upper and lower boundary of interval values. The first term in the objective function represents the cost during first-stage decision, where $x^{\pm}$ is a vector of first-stage decision variables. The second term is the expected penalties during the second-stage, wheresis a series of random events in the future, $y^{\pm}$ represents the decision variables based on the uncertain future events during the second-stage, and p_s is the probability of uncertain events with $\sum p_s = 1$. $c_j^{\pm}$ and $d_j^{\pm}$ are the regular cost and penalty cost coefficients respectively. $a_{rj}^{\pm}$, $a_{ij}^{\pm}$ and $e_{ij}^{\pm}$ are technical coefficients; $b_r^{\pm}$ and $\widehat{w}_{is}^{\pm}$ are resource limitation.

The above model can effectively account for stochastic uncertainties and dynamic features in long-term GEP through using interval values and discrete random variables. However, its solution does not reflect the risk attitude of decision makers. Robust optimization (RO), which originated from the pessimism decision rules proposed by Wald in 1950, can provide decision