Energy 116 (2016) 1145–1157

Contents lists available at ScienceDirect

Energy

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

Two-stage stochastic programming model for the regional-scale electricity planning under demand uncertainty

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ARTICLE INFO

Article history:
Received 17 June 2015
Received in revised form 18 September 2016
Accepted 22 September 2016
Available online 25 October 2016

Keywords:
Multi-region optimization model
Two-stage stochastic programming
Demand uncertainty
Monte Carlo simulation

ABSTRACT

Traditional electricity supply planning models regard the electricity demand as a deterministic parameter and require the total power output to satisfy the aggregate electricity demand. But in today's world, the electric system planners are facing tremendously complex environments full of uncertainties, where electricity demand is a key source of uncertainty. In addition, electricity demand patterns are considerably different for different regions. This paper developed a multi-region optimization model based on two-stage stochastic programming framework to incorporate the demand uncertainty. Furthermore, the decision tree method and Monte Carlo simulation approach are integrated into the model to simplify electricity demands in the form of nodes and determine the values and probabilities. The proposed model was successfully applied to a real case study (i.e. Taiwan's electricity sector) to show its applicability. Detail simulation results were presented and compared with those generated by a deterministic model. Finally, the long-term electricity development roadmap at a regional level could be provided on the basis of our simulation results.

1. Introduction

Traditional energy planning is based on the least-cost principles [1], in which the investment planning is according to deterministic mathematical programming techniques to determine the least-cost generation portfolio for projected future demand [2]. These traditional energy planning models have a common feature of overlooking the uncertainties. Today's environmental situation is extremely complex with high uncertainties and risks, and the electricity industry is also in an uncertain situation. If uncertainties are not effectively identified and included to the models, there can be a divergence between the simulation results and the optimal solution. Therefore, considerable research attention has recently been focused on assessing the uncertainty in energy system planning [3].

Further investigation of the existing studies on optimization under uncertain situations shows that common approaches to deal with the uncertainties also include scenario or sensitivity analysis, where the assumed values of key uncertainties are systematically varied in order to explore the range of possible outcomes. A major shortcoming of scenario or sensitivity analysis is due to the fact that it rarely captures the integration of possible outcomes of the uncertainties. Stochastic programming is regarded as a proper method for dealing with uncertainties in long-term strategic planning, due to the incorporation of flexibility within an optimization decision framework [4]. However, one practical limitation of the stochastic programming approach is the model size, which may reach gigantic proportions when complex decision trees are modeled. This drawback is much less acute now than in the past, thanks to the rapid progress of computing power and of algorithms. Hence, this methodology has been applied in various research areas, such as supply chain planning [5], process design and operation [6] as well as energy supply modeling [7]. Moreover, to address issues related to the optimal installed capacity investment and operation of an electrical system, several stochastic programming models have been proposed over the past few years. For instance, Albornoz et al. [8] formulated a two-stage stochastic integer programming model, for the planning of capacity expansion in a thermal system. The proposed model incorporated the uncertainty associated to the availability of the power plants. Heinrich et al. [9] incorporated aspects of flexibility to demand growth uncertainty into each future expansion alternative by introducing stochastic programming with recourse into the model. Li et al. [10]

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http://dx.doi.org/10.1016/j.energy.2016.09.112
0360-5442/

developed a multistage interval-stochastic regional-scale energy model for supporting electric power system planning. This developed model could deal with uncertainties expressed as both probability distributions and interval values existing in energy system planning problems. Mirkhani and Sabbohi [4] also formulated a multistage stochastic programming model for an energy system model, which the uncertainty of natural gas price was considered with the concept of Geometric Brownian Motion in the model.

Zhou et al. [11] presented the development and application of a two-stage stochastic model for the optimal design of distributed energy systems under energy demand and supply uncertainty, and a solution strategy which combined genetic algorithm and the Monte Carlo method was proposed. Tajeddini et al. [12] constructed a two-stage stochastic mixed integer linear programming model to maximize the expected profit of a virtual power plant operator in day-ahead and balancing energy markets considering the risk evaluation and minimization of non-dispatchable energy sources (e.g. wind and PV). Falsafi et al. [13] formulated a two-stage stochastic programming model to minimize total operating cost and air pollutants emission. The proposed model scheduled reserves provided by both generating units and responsive loads to cover uncertainty of wind power. Koltsaklis et al. [14] developed a multi-regional, multi-period mixed integer linear programming model, combining optimization techniques with a Monte Carlo method and demand response concepts. The proposed model incorporated the uncertainties associated to fuel prices, power units' availability, electricity imports and exports availability and price. In general, the aforementioned studies made a great effort in dealing with the uncertainties in an electrical system, and various uncertainties have been handled and reflected as particular forms, for instance, uncertainty in demand, uncertainty in economic parameters (e.g. energy prices) and uncertainty in technological parameters (e.g. the availability of the power plants). Energy demand uncertainty is attracted the most substantial attention among the various types of uncertainties [11,15]. Thus, consideration of the electricity demand uncertainty for an electrical system is of great importance.

In addition, existing stochastic programming models require the total power output must satisfy the aggregate electricity demand. To the best of our knowledge, only Refs. [10] and [14] considered regional characteristics in their stochastic planning models. However, the diversity of electricity demand in each region is quite different. This condition would be unfavorable for countries that exhibit electricity imbalance between northern and southern regions like Taiwan. For example, owing to the electricity imbalance situation in Taiwan, a large amount of power is required to be transmitted from the south to the north by 345-kV extra-high-voltage (EHV) lines. The abruptness of EHV lines could cause severe system instability. In order to minimize the investment cost and the transmission loss, and to prevent major blackout events, new generators should be installed close to load demanding areas to help achieve a balance between power supply and demand. Therefore, it is essential to incorporate regional electricity demand diversity into stochastic programming frameworks.

The objective of this paper is to construct a multi-region, two-stage stochastic programming model, combining optimization techniques with the decision tree method and Monte Carlo simulation approach. The developed model is designed to minimize the present value of total expected generation costs. The relevant constraints of conventional electricity planning models are also incorporated in model construction. In order to demonstrate the concept and the applicability of the proposed model, we use Taiwan's electricity sector as a case study. We then perform simulation analyses and observe optimal installed capacity per time period and region. Finally, the long-term electricity development roadmap at a regional level could be provided on the basis of our simulation results.

This model differs in two ways from previous applications of stochastic programming to the electricity supply planning (i.e. the main novelty of the proposed model). First, we explicitly address the issue of the generation technology portfolios from a regional perspective in stochastic programming frameworks, and extend the formulation to reflect regional electricity demand diversity, while previous models merely require total power output to satisfy the aggregate electricity demand. Second, we incorporate decision tree and Monte Carlo simulation method to determine future annual electricity demands and their path probabilities, rather than assigning path probabilities arbitrarily. The following section begins with an overview of relevant methodology. Section 3 describes the model formulation. Section 4 contains data sources and adjustments. Section 5 provides major results of the research, and Section 6 presents the conclusion.

2. Methodology description

2.1. Two-stage stochastic programming

In stochastic programming frameworks, the most common approach to sequential decision making under uncertainty is two-stage stochastic programming. Two-stage stochastic problem means a stochastic programming problem with recourse. Initially, a decision can be made with incomplete information on random parameters, and after the values of the random variables are known, recourse action can be taken in the second stage. The fundamental idea of two-stage stochastic programming is the concept of recourse that refers to the ability to take corrective actions after a random event has taken place [16]. A general two-stage stochastic programming model can be expressed as follows [7]:

$$\min z = cx + E_\omega[fy^\omega]$$

Subject to

$$Ax = b$$

$$-B^\omega x + Dy^\omega = d^\omega$$

$$x,\ y^\omega \geq 0$$

$$\omega \in \Omega = \{1, 2, \ldots.., W\} \quad (1)$$

Where x is the first-stage decision variables; y^ω is the second-stage decision variables; f is the second-stage objective coefficients; B^ω, d^ω, D are parameters of the second-stage constraints; ω is a set of possible realizations of the uncertainty parameter and E_ω is the mathematical expectation with respect to ω.

2.2. Decision tree method

Although two-stage stochastic programming model can involve uncertain parameters, the main problem is to perform optimization directly in terms of continuous distributions. Therefore, in most cases the continuous distributions are approximated by discrete distributions with possible realizations for the random variables [17]. Generally, a decision tree is a set of nodes and branches used in stochastic programming frameworks. Each node in the tree stands for a possible state at a specific point in time and a position where a decision can be made. An arc emanating from a node indicates a possible realization of the uncertain variables from that state. The root node is the first node in the decision tree standing for the