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Regional-scale electric power system planning under uncertainty—A multistage interval-stochastic integer linear programming approach

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ABSTRACT

In this study, a multistage interval-stochastic regional-scale energy model (MIS-REM) is developed for supporting electric power system (EPS) planning under uncertainty that is based on a multistage interval-stochastic integer linear programming method. The developed MIS-REM can deal with uncertainties expressed as both probability distributions and interval values existing in energy system planning problems. Moreover, it can reflect dynamic decisions for electricity generation schemes and capacity expansions through transactions at discrete points of a multiple representative scenario set over a multistage context. It can also analyze various energy-policy scenarios that are associated with economic penalties when the regulated targets are violated. A case study is provided for demonstrating the applicability of the developed model, where renewable and non-renewable energy resources, economic concerns, and environmental requirements are integrated into a systematic optimization process. The results obtained are helpful for supporting (a) adjustment or justification of allocation patterns of regional energy resources and services, (b) formulation of local policies regarding energy consumption, economic development, and energy structure, and (c) analysis of interactions among economic cost, environmental requirement, and energy-supply security.

1. Introduction

Effective planning of electric power systems (EPSs) plays an important role for electric utilities as well as whole human activities (Dentcheva and Roemisch, 1998). Nowadays, EPS planning is a challenging task for decision makers in many regions, due to the diversity of supply technology options available (influencing model size and complexity), the temporal and/or spatial evolutions of parameters over medium- to long-term time horizons, the dynamic variation of systems' conditions, the environmental and social arguments, as well as various uncertainties during the planning process (Murto, 2003; Heinricha et al., 2007). Previously, a number of systems analysis techniques were employed for assisting development of long-term energy management plans (Mazumdar and Chrzan, 1995; Shrestha et al., 1998; Malik, 2001; Terrados et al., 2007; Cai et al., 2008a). Among them, optimization methods were employed for directly supporting decision making under varying system conditions (De Musgrove, 1984; Kydes, 1990; Lehtila and Pirila, 1996; Cormio et al., 2003; Jebaraj and Iniyanb, 2004). For example, De Musgrove (1984) introduced a linear programming method into the MARKAL model to analyze minimum discounted cost configurations for the Australian energy system during the period of 1980–2020. Kydes (1990) discussed two optimization models to examine inter-fuel substitutions in the context of constraints on the availability of competing resources and technologies. Lehtila and Pirila (1996) formulated a bottom–up energy system optimization model to support policy planning for the sustainable use of energy in Finland that considered biomass use for energy, power, heat generation, emissions, and the end use of energy. An optimal renewable energy model that minimizes the cost/efficiency ratio and determines the optimum allocation of different renewable energy resources for various end uses was proposed by Iniyan and Sumathy (2000).

In summary, the above conventional optimization methods were useful for planning energy systems with considerations of a number of impact factors (e.g. economic objective, environmental requirement, and policy regulation); however, they had difficulties in tackling various uncertainties existing in the energy system planning problems. In fact, in EPS management and planning problems, many system parameters and their interrelationships are often associated with uncertainties presented in terms of multiple formats. Moreover, many uncertainties could be further multiplied by complexities in a variety of system components as

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well as their associations with economic penalties if the promised targets are violated (Li et al., 2006a, 2008a). Furthermore, increasing deregulation of power markets can further amplify the uncertainties and complexities.

As a result, a number of modeling approaches that could tackle the above uncertainties and complexities in the EPS planning problems were developed (Pereira and Pinto, 1991; Liu et al., 2000; Dupačová, 2002; Sadeghi and Hosseini, 2006; Muela et al., 2007; Liu, 2007; Lin and Huang, 2008; Lin et al., 2008). Among them, many researchers paid much attention to stochastic programming methods, which could directly integrate uncertain information expressed as probability distributions into the modeling formulations. For example, Pereira and Pinto (1991) proposed a stochastic optimization approach for the planning of a multi-reservoir hydroelectric system under uncertainty, associating a given probability to each range of inputs that occurred at different stages of an optimization horizon. Römisch and Schultz (1995) developed an optimization model using multistage stochastic programming (MSP) for the optimal dispatch of electric power under uncertain demands in a generation system comprising thermal and pumped storage hydro plants. Takriti et al. (1996) proposed a MSP-based model and a solution technique for the problem of generating electric power when demands were uncertain. Numerical results indicated significant savings in the cost of operating power-generating systems when a stochastic model is used instead of a deterministic model. Liu et al. (2000) proposed a hybrid inexact chance-constrained mixed-integer linear programming method for non-renewable energy resource management under uncertainty, with an objective of maximizing economic return under constraints of resource availability and environmental regulations. Nürnberg and Römisch (2002) developed a two-stage stochastic programming model for short- or mid-term cost-optimal electric power production planning, considering the power generation in a hydro-thermal generation system under uncertainty in demand (or load) and prices for fuel and delivery contracts. In order to tackle uncertainty in flow to reservoirs and prices in spot and contract markets, Kristoffersen (2007) developed many MSP-based optimization models and successfully applied them to power systems. Within the framework of multistage mixed-integer stochastic linear programming, Fleten and Kristoffersen (2008) developed an effective production plan for a price-taking hydropower plant operating under uncertainty.

Generally, MSP is useful for tackling medium- to long-term planning problems in which an analysis of policy scenarios is desired and the right-hand-side coefficients are random with known probability distributions within a multistage context. The fundamental idea of MSP is recourse, expressing the ability to take corrective actions in each time stage based on the uncertainty sequentially realized so far. The primary advantage of the scenario-based MSP is the flexibility it offers in modeling the decision process and defining scenarios, particularly if the state dimension is high (Birge, 1985; Li et al., 2006b). However, the MSP can hardly tackle independent uncertainties of the model's left-hand sides and cost coefficients; moreover, the quality of available information about uncertainties is often not satisfactory enough for establishing probability distributions. Furthermore, even if the probability distributions are available, it could be difficult to reflect them in large-scale stochastic models (Huang and Loucks, 2000; Li et al., 2006a).

Interval linear programming (ILP) is an alternative for handling uncertainties in objective functions and system constraints as well as those that cannot be quantified as probability distributions, since interval numbers are acceptable as its uncertain inputs (Li et al., 2008a, b). It improves upon the existing methods with the following natures: (i) it allows uncertainties to be directly communicated into the optimization process and resulting solutions, (ii) it does not lead to more complicated intermediate models, and thus has a relatively low computational requirement, and (iii) it can be easily integrated with other optimization methods (Huang et al., 1992, 1995a, b; Cai et al., 2008b). In the past decade, ILP was extensively applied to a variety of environmental management and planning problems (e.g. municipal solid waste, water resources, and air quality management as well as energy system planning; Huang et al., 2000, 2001; Huang and Chang, 2003; Li et al., 2006a, b, 2008a, b; Liu, 2007; Lin and Huang, 2008; Lin et al., 2008). For example, Liu (2007) proposed an inexact two-stage energy system planning model that integrated ILP and two-stage stochastic programming within a general optimization framework. Lin and Huang (2008) developed an energy system planning model using ILP for the optimization problem of energy allocation and capacity expansion within a regional jurisdiction, where interval solutions allow for detailed interpretation of the trade-off between environmental pollution risks and economic objectives. Nevertheless, ILP has the following weaknesses: (a) it may become infeasible when the model's right-hand sides are highly uncertain and (b) it cannot tackle uncertainties expressed as possibilistic and/or probabilistic distributions, leading to the loss of valuable information in many real-world planning problems (Huang et al., 1992, 2001).

Therefore, it is desired that an integrated optimization method be developed for handling uncertainties and complexities in the EPS planning. The objective of this study is thus to develop a multistage interval-stochastic regional-scale energy model (MIS-REM) for supporting EPS planning under uncertainty that is based on a multistage interval-stochastic integer linear programming method. Uncertainties existing in model stipulations and coefficients, expressed as not only probability distributions but also interval values, are directly included in the model and communicated into the optimization process, such that solutions reflecting the inherent uncertainties can be generated. More importantly, it will be used for reflecting dynamics in terms of decisions for electricity generation schemes through transactions at discrete points of a complete scenario set over a multistage context, quantitatively analyzing multiple policy scenarios that are associated with economic penalties when promised targets are violated, identifying optimal patterns for energy resource utilization, and helping formulate efficient EPS at a regional scale. A case study will then be provided for demonstrating applicability of the developed model. In detail, this study will (1) formulate such a MIS-REM that integrates renewable and non-renewable energy resource supply, electricity generation, conversion, and consumption into a systematic optimization process, (2) apply the MIS-REM to long-term regional-scale EPS planning problems, where uncertain factors relating to resources, environmental and socio-economic objectives and constraints are considered and incorporated into the MIS-REM to generate decision alternatives for supporting an effective energy system planning under uncertainty, and (3) analyze the generated results and discuss the applicability of the developed model.

2. Modeling formulation

2.1. Development of multistage interval-stochastic regional-scale energy model

Considering a typical regional-scale electric power system wherein three main components are comprised, including the energy resource supply sector, which provides energy resources with different availabilities, including diverse renewable and non-renewable resources to the system; the energy conversion sector,