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Planning regional-scale electric power systems under uncertainty: A case study of Jing-Jin-Ji region, China

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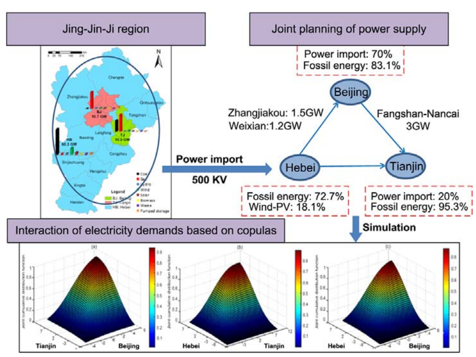
HIGHLIGHTS

- A copula-based stochastic fuzzy-credibility programming method is proposed.
- Multi-uncertainty and interactions among multiple random variables are examined.
- Its applicability can be verified in planning the EPS of Jing-Jin-Ji region.
- Solutions of various scenarios and different credibility levels are analyzed.
- CSFP-REPS can provide multiple joint planning strategies for the REPS.

GRAPHICAL ABSTRACT



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ABSTRACT

In this study, a copula-based stochastic fuzzy-credibility programming (CSFP) method is developed for planning regional-scale electric power systems (REPS). CSFP cannot only deal with multiple uncertainties presented as random variables, fuzzy sets, interval values as well as their combinations, but also reflect uncertain interactions among multiple random variables owning different probability distributions and having previously unknown correlations. Then, a CSFP-REPS model is formulated for planning the electric power systems (EPS) of the Jing-Jin-Ji region, where multiple scenarios with different joint and individual probabilities as well as different credibility levels are examined. Results reveal that electricity shortage would offset [4.8, 5.2]% and system cost would reduce [3.2, 3.3]% under synergistic effect scheme. Results also disclose that the study region's future electricity-supply pattern would tend to the transition to renewable energies and the share of renewable energies would increase approximately 10% over the planning horizon. Compared to the conventional stochastic programming, the developed CSFP method can more effectively analyze individual and interactive effects of multiple random variables, so that the loss of uncertain information can be mitigated and the robustness of solution can be enhanced. Moreover, based on the main effect analysis and regression analysis, CSFP-REPS can provide multiple joint planning strategies in a cost- and computation-effective way. Findings are useful for reflecting interactions among multiple random variables and disclosing their joint effects on modeling outputs of REPS planning problems.

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1. Introduction

With the growing blackouts frequency and rapid socioeconomic development, electricity demand-supply security is becoming particularly urgent for planning regional-scale electric power systems (REPS). Energy supply, resource conservation, and environmental protection continue to be the major concerns for many countries throughout the world [1,2]. Although China has made great efforts to improve energy utilization efficiencies, upgrade power transmission infrastructures, expand power conversion facilities, as well as develop renewable energies, two major hurdles still restrict effectively planning electric power systems (EPS) [3–5]. The electricity-demand target of REPS is regulated by each individual EPS instead of being addressed as a group. When a new target electricity-demand is added, a magnitude of extra effort (e.g., investment, human labor, and land use) is required. However, the possible adverse impacts (meeting one electricity-demand while sacrificing the other's energy resources) among various individual EPS schemes can lead to a low efficiency of EPS planning resource input [6]. Besides, for each individual EPS, the main solutions to satisfy the tremendous electricity shortage are capital-investment based measures (e.g., capacity expansion and power import). Although the measures can bring positive effects on one individual EPS, they may impose negative effects on the other EPS simultaneously [7,8].

Therefore, to facilitate the achievement of multiple electricity-demand targets in a cost-effective way, joint planning for REPS is desired [9]. Joint planning for REPS can effectively integrate electricity demands of multiple EPS into one general framework, which not only brings conjunct satisfaction effects of REPS but also produces individual satisfaction effects for each EPS simultaneously [10]. Previously, a number of systems analysis approaches for planning REPS were advanced [11–16]. For example, Devlin and Talbot [11] used dynamic programming for planning the renewable energy resources in the EPS of Ireland, where the changed transport costs in each time horizon were obtained. Sun et al. [15] utilized a static deterministic linear model for planning the China's REPS development, in which real energy use patterns among interregional energy spillover effects were examined. Generally, the above studies for planning REPS are mainly based on deterministic analysis methods through converting into a linear programming (LP) model; they also narrow themselves in planning the REPS with conjunct targets for each individual EPS, which are incapable of reflecting the complex interactions among REPS [17]. For a real-world REPS, the unique energy, environmental and economic features of individual EPS could influence each other, which enforce the REPS become more complicated [18,19]. Besides, some system parameters are not available as deterministic values owing to the incompleteness or impreciseness of observed information. Previously, a number of inexact optimization methods were developed for planning the REPS in response to such complexities and uncertainties [20–24]. For example, Narayan and Ponnambalam [23] developed a risk-averse stochastic programming (SP) model for planning the EPS, where random parameters of uncertain nature resources, imprecise renewable energy generation and cost as well as dynamic demand needs were tackled. Lotfi and Ghaderi [25] proposed a novel possibilistic price-based mixed integer linear programming approach for planning the mid-term electric power systems, in which uncertainties in the objective function and constraints were solved based on possibilistic distributions. Wang et al. [26] proposed a multistage joint-probabilistic chance-constrained fractional programming approach for planning the provincial EPS of Saskatchewan (Canada), where joint probabilities existed in carbon emissions were reflected.

Generally, stochastic programming (SP) has advantage in dealing with random variables with known probability distributions; fuzzy programming (FP) is effective for representing the possible degree of event occurrence for imprecise data described by fuzzy possibility distributions [27–29]. However, few of them are focused on analyzing interactive relationships among multiple random parameters in the REPS. Besides, joint-probabilistic programming (JPP) for reflecting interactive relationships among a set of probabilistic constraints are based on assumptions that all of random variables employed to probabilistic constraints are normally and independently distributed [30]. In practical REPS planning problems, multiple random variables may present different probability distributions and the associated correlation may be previously unknown [31]. In detail, one region may contain several individual EPS with each at an urban-scale; each individual EPS has its unique characteristics in population, resources, economy, environment and geographic location. The previous studies are limited to these assumptions, and may be not suitable for the cases where random variables present different probability distributions with unknown correlations. Copula approach for modeling multivariate joint distributions was proposed by Sklar in 1959, which can characterize multivariate joint distributions by its respective marginal distributions and bind them together independent of the types of individual marginal distributions through using copula functions [32,33].

Therefore, this study aims to develop a copula-based stochastic fuzzy-credibility programming (CSFP) method for the joint planning of regional-scale electric power systems (REPS). CSFP will integrate copula-based stochastic programming (CSP), fuzzy-credibility constrained programming (FCP), and interval-parameter programming (IPP) within a mixed-integer linear programming (MILP) framework. Then, a CSFP-REPS model is formulated to planning the REPS of Beijing, Tianjin and Hebei province (abbreviated as "Jing-Jin-Ji" region). In CSFP-EPS, a series of scenarios with different joint and individual probabilities as well as different credibility levels will be considered. Results will provide decision supports for: (a) reflecting uncertain interactions among multiple random variables and disclosing their impacts on system outputs; (b) achieving tradeoffs among system violation risk, environmental requirement and system cost; (c) identifying joint planning strategies of Jing-Jin-Ji region in a cost- and computation-effective way.

2. Development of CSFP-REPS model

2.1. Copula-based stochastic fuzzy-credibility programming

A decision maker is responsible for allocating electricity-supply patterns, capacity expansions and pollutant mitigation with a minimum system cost over a long-term planning horizon [34]. In the REPS, the total electricity demand may vary from each individual EPS in each period, and the relationship of electricity demands among individual EPS may be previously unknown. These can be presented as random variables, and the interactive relationship among electricity demands in individual EPS can be reflected through copulas [35–37]. Copula functions connect univariate marginal distribution functions with the multivariate probability distribution:

$$F(x_1,x_2,...,x_n) = C\,(F_{X_1}(x_1),F_{X_2}(x_2),...,F_{X_n}(x_n)) \tag{1}$$

where $F_{X_1}(x_1),F_{X_2}(x_2),...,F_{X_n}(x_n)$ are marginal distributions of electricity demands $(X_1,X_2,...,X_n)$. If these marginal distributions are continuous, a single copula function C exists, which can be written as [38]:

$$C(u_1,u_2,...,u_n) = F(F_{X_1}^{-1}(u_1),F_{X_2}^{-1}(u_2),...,F_{X_n}^{-1}(u_n)) \tag{2}$$

Based on Chen et al. [33], Simic and Dabic-Ostojic, [39], a general copula-based stochastic programming (CSP) model can be formulated as:

$$\text{Min } E = \sum_{i=1}^{I}\sum_{k=1}^{K}\sum_{t=1}^{T} d_{i,k,t}x_{i,k,t} \tag{3a}$$

subject to:

$$Pr\left\{\sum_{k=1}^{K} a_{i,k,t}x_{i,k,t} \leqslant (b_{i,t}^{p_{i,t}})\right\} \geqslant 1-p_{i,t}\ ,\quad \forall\ i,t \tag{3b}$$

[constraints of individual electricity demands]