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Multi-year stochastic generation capacity expansion planning under environmental energy policy

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HIGHLIGHTS

- A methodology for policy assessment was developed using a multi-stage stochastic program.
- Carbon tax and renewable portfolio standard are applied as energy environmental policies.
- Correlated wind and load samples are generated via Gaussian copula.
- A Scenario tree is constructed with i.i.d. random samples and reduced by GAMS/SCENRED2.
- A long-term stochastic generation capacity expansion model is presented.

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ABSTRACT

We present a multi-year stochastic generation capacity expansion planning model to investigate changes in generation building decisions and carbon dioxide (CO_2) emissions under environmental energy policies, including carbon tax and a renewable portfolio standard (RPS). A multi-stage stochastic mixed-integer program is formulated to solve the generation expansion problem. The uncertain parameters of load and wind availability are modeled as random variables and their independent and identically distributed (i.i.d.) random samples are generated using the Gaussian copula method, which represents the correlation between random variables explicitly. A multi-stage scenario tree is formed with the generated random samples, and the scenario tree is reduced for improved computation performance. A rolling-horizon method is applied to obtain one generation plan at each stage.

1. Introduction

A multi-year generation planning study provides optimal timing as well as optimal capacity for generation system expansion, which helps power system planners to make decisions about investments in generation capacity.

The planning horizon of a generation planning model may be one year, a couple of years, or up to several decades. If intervening years before the end of the horizon are not represented, and only the final year of the horizon is represented, then the model can be referred to as a "target-year model." In a typical formulation of a target-year model, a generation unit is built if the annual savings (or the avoided curtailment) due to building the unit exceeds its annualized investment costs. Those models can be found in [1–3].

In most cases, a multi-year planning model that considers several stages of generation capacity expansion may offer more specified, supportive information for decision-making as compared to a target-year model. Such long-term planning models are developed to represent a particular circumstance or various regulations, e.g., [4–6], where [4] considers a market environment in which generators compete with one another, and [5] includes probabilistic load and unit outage by using a load duration curve and unit outage distribution. Reference [6] presents a mixed integer programming formulation for multi-year generation planning and discussed several aspects that can be considered in resource planning, such as transmission constraints, possible uncertainty in power systems, and competition in the market environment.

Impacts on generation capacity needs in accordance with environmental policies were investigated through optimization models in [7–10]. A long-term generation capacity expansion simulation model considering renewable resources–wind and solar–was presented in [7], where the correlation between load and the output

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Nomenclature

Sets/Indices

$t \in \mathbf{T}$ stages
$g \in \mathbf{G}$ all existing generators
$c \in \mathbf{G^c}$ conventional generators, $\mathbf{G^c} \subset \mathbf{G}$
$f \in \mathbf{G^f}$ fossil-fuel generators, $\mathbf{G^f} \subset \mathbf{G}$
$w \in \mathbf{G^w}$ wind generators, $\mathbf{G^w} \subset \mathbf{G}$
$n \in \mathbf{G_n}$ all candidate generators
$i \in \mathbf{G_n^c}$ candidate conventional generators, $\mathbf{G_n^c} \subset \mathbf{G_n}$
$j \in \mathbf{G_n^f}$ candidate fossil-fuel generators, $\mathbf{G_n^f} \subset \mathbf{G_n}$
$k \in \mathbf{G_n^w}$ candidate wind generators, $\mathbf{G_n^w} \subset \mathbf{G_n}$
$\omega, \omega^{child}, \omega^{parent} \in \mathbf{\Omega}$ realizations of random variable, nodes
$(t, \omega) \in \mathbf{\Lambda_s}$ stage and node mapping set
$(\omega^{child}, \omega^{parent}) \in \mathbf{\Lambda_a}$ child and parent node mapping set

Data/Parameters

e_f, e_j CO_2 emissions rate of generator f and j (ton/MW h)
o_{tc}^r, o_{ti}^r cost for procuring reserve from generator c and i at stage t ($/MW h)
o_{tc}, o_{ti} operating cost for generator c and i at stage t ($/MW h)
RS fixed reserve requirements (MW)
α_{tn} over-night building cost for candidate generator n at stage t ($)
β, β^r penalty cost on load-shedding and unmet reserve ($/MW h)
δ_t CO_2 tax rate for energy generated by fossil-fuel generator at stage t ($/ton)
γ penalty cost on unfulfillment of RPS requirements ($/MW h)
r_t RPS requirements at stage t ($\times 100\%$)
P_c^{max} capacity of conventional generator c (MW)
$P_w^{max}(\xi_w^\omega), P_k^{max}(\xi_w^\omega)$ realized availability of wind generator w and candidate generator k (MW)
P_i^{max} capacity of candidate conventional generator i (MW)
h Opearing hours for a year (h)
p^ω Probability of realization ω

Random variables

ξ_d system load (MW)
ξ_w available wind power (MW)

Binary decision variables

$x_{tn}^\omega, x_{ti}^\omega, x_{tk}^\omega$ decision to build candidate generator n, i, k

Continuous decision variables

z_{tn}^ω subsequent building decision for candidate n at stage t
P_{tg}^ω, P_{tc}^ω, P_{tw}^ω generation of generator g, c, and w (MW)
R_{tc}^ω, R_{ti}^ω reserve procured from generator c and i (MW)
P_{tn}^ω, P_{ti}^ω, P_{tk}^ω generation of candidate wind generator n, i, and k (MW)
U_t^ω load-shedding (MW)
V_t^ω unmet reserve (MW)
Y_t^ω unfulfillment of RPS requirements (MW)

of renewable resources was included in the simulation model, and short-term and long-term planning models were compared. In reference [8], multiple objectives including minimizing CO_2 emissions were introduced in the mathematical formulation. Optimal decisions based on different objectives provide the system planner with various combinations of planning decisions. Constraints restricting CO_2 emissions were applied to the optimization model in [9]. Ref. [10] investigated a multi-objective linear programming model with minimizing total generation cost and energy consumption as well as greenhouse gas emissions, and a long-term simulation was performed.

Stochastic generation planning models considering uncertainty that may exist in power systems are presented in [2,11,3,12–14]. Ref. [2] introduced a two-stage stochastic generation capacity expansion model with uncertain generation capacity due to unit unavailability and load uncertainty. Two different sampling methodologies were compared, and the approximated solution was evaluated by the solution quality assessment.

Uncertainty of demand was incorporated in the generation planning model in [11], and an optimal decision for a horizon of 14 years was investigated using a two-stage stochastic program. The original scenario was reduced to avoid computational difficulties.

To represent increasing amounts of uncertain renewable resources and high environmental concerns about greenhouse gas emissions, stochastic generation capacity expansion for the system with uncertainties was simulated including applying a carbon tax and renewable portfolio policies [3]. This formulation employed a two-stage stochastic program.

Stochastic dynamic programming was applied in [12,13] in order to solve a long-term generation planning problem, where energy demand and oil prices were modeled as random variables, and their correlation was reflected [12]. The uncertainty of electric load and generator outage capacity was taken into account in [13], where the random variables were assumed to be independent of each other.

Ref. [14] used multi-stage stochastic programming with a reduced scenario set for hydro inflows to the reservoir. The obtained optimal values with different numbers of reduced scenario sets were evaluated using the discrepancy between the suggested metrics such as value of stochastic solutions and wait-and-see solutions.

Uncertainty of electric load has been modeled in most stochastic power systems. As the system changes to accommodate more renewable resources, uncertainty of renewable resources increases in significance. If the correlation between uncertain parameters is reflected the accuracy of model may be improved. Although the correlation between electric load and wind is represented in some models [1,3], a single target year model was implemented so that the decision of timing to build generators were not provided. This study generalizes two-stage stochastic programs used in [3] to the multi-stage context.

As various energy environmental policies such as reducing greenhouse gas emissions are under consideration in many countries, a well-defined long-term generation capacity expansion simulation model is needed for the evaluation of policy effectiveness and generation mix in the long run. Therefore, we propose a multi-year stochastic generation system planning model with consideration of correlation between defined random variables.

The main contribution of our work is the development of a multi-stage stochastic model using two random parameters, load and wind availability, with an explicit representation of their dependence. The multi-year decision process is modeled with the given scenario tree, where the scenario tree size is reduced for efficient problem solving. The random samples of wind and load for the tree construction are generated by Gaussian copula to represent the correlation between wind and load, which enables Monte