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Sustainable resource planning in energy markets

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HIGHLIGHTS

- Sustainable resource planning with the consideration of expected transmission network expansion.
- Incomplete information non-cooperative game-theoretic method for GEP.
- Maximizing utility value whiling considering merits of having various generation portfolios.
- Minimizing risk of investment using renewable generation options.
- Application of the stochastic approach for evaluating the unpredictability of opponent payoffs and commodity values.

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ABSTRACT

This study investigates the role of sustainable energy volatility in a market participant's competitive expansion planning problem. The incomplete information non-cooperative game-theoretic method is utilized in which each generation company (GENCO) perceives strategies of other market participants in order to make a decision on its strategic generation capacity expansion. Sustainable generation incentives, carbon emission penalties, and fuel price forecast errors are considered in the strategic decisions. The market clearing process for energy and reserves is simulated by each GENCO for deriving generation expansion decisions. A merit criterion (i.e., the utility value) is proposed for a more realistic calculation of the expected payoff of a GENCO with sustainable energy resources. Finally, the impact of transmission constraints is investigated on the GENCO's expansion planning decision. The case studies illustrate the effectiveness of the proposed method.

1. Introduction

Market participants seek to maximize their payoffs by optimizing their investment on sustainable energy resources [1]. A market participant's decision is based on its own investment strategies as well as its imperfect knowledge of other participants' strategies. Therefore, self-interested stakeholders learn and adapt to the perceived behaviors of other participants in order to maximize their payoffs in competitive markets. In a market, the independent system operator's (ISO's) objective is to supply the demand at the minimum cost while maintaining a pre-specified level of system reliability.

Generation expansion planning (GEP) has been broadly examined in the literature. Using the Benders decomposition method, a profit-based generation resource planning was discussed in [2], which considered the economics and the reliability of market operation. Lagrangian relaxation algorithm was applied in [3] to relax complicated coupling constraints into the objective function of planning problems and obtain locational capacity signals. An agent-based model was applied in [4] to simulate an expansion planning approach which took into account interactions among multiple agents in electricity markets. The paper considered an incomplete information model where individual generators (agents) do not have information of its opponents. One of the early studies on the application of non-cooperative game theory was presented in [5]. The paper simplified the problem by assuming the availability of complete information to all opponents. The competitive behavior of GENCOs in an electricity market was considered in [6] by applying a game theoretic method, and a co-evolutionary algorithm was proposed to model GENCOs as agents. Applying artificial intelligence algorithms may lead to non-convergence or sub-optimal results in case of large study systems with numerous market participants, while the simulation time is always a concern when using such methods. Furthermore, GENCOs can receive misleading profit signals by neglecting expected transmission expansions in the system and/or uncertain

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Nomenclature

Indices

C superscript index for candidate generation units or transmission lines
E superscript index for existing units or lines
g subscript for generation companies (GENCOs)
i index for generating units
j index for transmission lines
m, n subscript for bus numbers
NW index for thermal units
s index for scenarios
t subscript for time periods
W index for wind units

Parameters

α incentive rate factor
σ standard deviation of an uncertain quantity
CGW number of candidate wind generation units
$CGNW$ number of candidate non-wind generation units
$Cap_{\max}$ GENCOs' total available expansion capacity
DT_t duration of planning period t
EG_g number of committed generating units of GENCO g
$E(\cdot)$ expected value
$EC(\cdot)$ emission cost
FOR forced outage rate
$IC(\cdot)$ levelized investment cost
$INC(\cdot)$ incentive payment
NB number of buses
NGC number of GENCOs
NT number of planning periods
$E(\cdot)$ outage cost
OC average operating cost
$p(t_i)$ probability when participant i's type is t_i
$p(\mathbf{t}_{-i}|t_i)$ conditional probability when GENCO i's type is t_i and its opponents' type is $\mathbf{t}_{-i}$
$p(s)$ probability of scenario s
r investment payoff
RC reserve cost
RP revenue from the energy market
PR revenue from the reserve market
Sc planning scenario
S_o opponents' strategy
S_s self-strategy
S_t GENCOs' final expansion strategy
ty_i GENCO i's type
$\mathbf{ty}_{-i}$ type of GENCOi's opponents
$\mathbf{TY}_i$ the set of GENCO i's types
$\mathbf{TY}_{-i}$ the set of types of GENCOi's opponents
U utility value
$UY_{mn,ts}$ status of transmission line $m-n$ in time t of scenario s; 0 if on outage, otherwise 1
UX_{gts} status of GENCO g in time t of scenario s; 0 if on outage, otherwise 1
Y_{jt} installation status of transmission line j in year t
γ_j phase shifter angle on line j

Decision variables

PC load shedding quantity
PG dispatched capacity in the energy market
$PG^C_{\max}$ capacity of a candidate generation unit
PL power flow of a transmission line
PR reserve capacity bid to the ancillary service market
Q_R reserve capacity price
X generation unit's expansion type
θ bus angle
$\lambda_p,\ \lambda_R$ Lagrangian multipliers

Matrices and vectors

$\mathbf{A}$ bus-unit incidence matrix
$\mathbf{B}$ bus-load incidence matrix
$\mathbf{K}$ bus-branch incidence matrix
$\mathbf{P}$ real power output vector
$\mathbf{PC}$ load shedding vector
$\mathbf{PD}$ load vector
$\mathbf{PL}$ real power flow vector
$\mathbf{UY}$ transmission line availability status vector

factors. A deterministic model was applied in [7], which used game theory to investigate the strategic interaction among GENCOs and transmission companies (TRANSCOs) in a restructured market environment. A multi-agent expansion model in [8] investigated interactions among self-interested GENCOs in electricity markets. A hybrid GEP algorithm that utilized a combination of game theory and genetic algorithm was presented in [9]. In practice, expansion planning forms a first-price sealed-bid auction [10] problem in which individual market participants have a perfect knowledge of their own payoffs and strategies, but lack such a complete information on other participants [11]. The expansion planning problem was modeled as an incomplete information environment [12], in which a participant could potentially lower its payoff if it does not consider the opponents' strategies. A stochastic mixed-integer linear programming (MILP) approach was applied in [13] to form a structure for making profit-maximization based expansion decision in a liberalized market. Ref. [13] also performed a thorough literature review in the area of generation investment.

Sustainable resources are abundant, environment friendly, and volatile [14]. Sustainability prohibits the depletion of energy resources and the accumulation of residues [15], and is subjected to incentive credits in many energy markets. Higher fuel prices, long permitting process, and environmental constraints have limited the planning options for large fossil-fuel power plants. A multi-objective model for the hybrid generation and transmission corridors expansion planning incorporating certain sustainable energy resources was presented in [16]. The model is applicable to centralized power systems for minimizing the total investment and operating costs. Hybrid expansion planning of generation and transmission was examined in [17]. Results of the study in [17] clearly indicate that despite decisions of generation and transmission planning are made by independent entities, the physical connection between generation and transmission expansion necessitates considering the mutual impacts of these sectors. The approach in [18] showed that a mix of sustainable energy resources could lead to lower generation costs despite their higher investment costs. To overcome such constraints, participants are increasingly looking into sustainable options for optimizing generation strategies and diversifying generation portfolios. In the United States, renewable portfolio standards (RPSs) are mandated in many states. In addition, production tax credit (PTC) and investment tax credit (ITC) are made available to encourage the development of various types of sustainable generation resources. Complementary technologic and economic tools are also being utilized to mitigate the carbon emission of electrical systems [19]. Carbon emission tax policies have been initiated by several ISOs