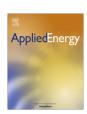


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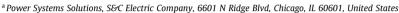
journal homepage: www.elsevier.com/locate/apenergy



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Sustainable resource planning in energy markets

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- 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.

ARTICLE INFO

Article history: Received 7 February 2014 Received in revised form 13 May 2014 Accepted 17 July 2014

Keywords: Sustainable energy resource Expansion planning Energy market Generation company Game theory

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.

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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 RP revenue from the energy market PR revenue from the reserve market **Indices** Sc planning scenario Csuperscript index for candidate generation units or S_o opponents' strategy transmission lines Ss self-strategy Е superscript index for existing units or lines S_t GENCOs' final expansion strategy subscript for generation companies (GENCOs) g ty_i GENCO i's type index for generating units type of GENCOi's opponents ty_{-i} index for transmission lines TY_i the set of GENCO i's types m.n subscript for bus numbers \mathbf{TY}_{-i} the set of types of GENCOi's opponents NW index for thermal units П utility value index for scenarios S UY_{mn.ts} status of transmission line m - n in time t of scenario s; subscript for time periods t 0 if on outage, otherwise 1 W index for wind units **UX**_{gts} status of GENCO g in time t of scenario s; 0 if on outage, otherwise 1 **Parameters** Y_{it} installation status of transmission line *j* in year *t* incentive rate factor α phase shifter angle on line j γ_i standard deviation of an uncertain quantity **CGW** number of candidate wind generation units Decision variables number of candidate non-wind generation units **CGNW** PC load shedding quantity GENCOs' total available expansion capacity Cap_{max} dispatched capacity in the energy market PG DT_t duration of planning period t PG_{\max}^{C} capacity of a candidate generation unit EG_g number of committed generating units of GENCO g PL power flow of a transmission line expected value $E(\cdot)$ PR reserve capacity bid to the ancillary service market $EC(\cdot)$ emission cost reserve capacity price Q_R FOR forced outage rate Χ generation unit's expansion type $IC(\cdot)$ levelized investment cost θ bus angle $INC(\cdot)$ incentive payment Lagrangian multipliers NB number of buses NGC number of GENCOs NT number of planning periods Matrices and vectors $E(\cdot)$ outage cost Α bus-unit incidence matrix OC B bus-load incidence matrix average operating cost $p(t_i)$ probability when participant i's type is t_i K bus-branch incidence matrix $p(\mathbf{t}_{-i}|t_i)$ conditional probability when GENCO i's type is t_i and its P real power output vector PC opponents' type is \mathbf{t}_{-i} load shedding vector probability of scenario s PD p(s)load vector investment payoff PL real power flow vector RC reserve cost 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 mixedinteger 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 lim-

ited 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

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