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Competition, risk and learning in electricity markets: An agent-based simulation study

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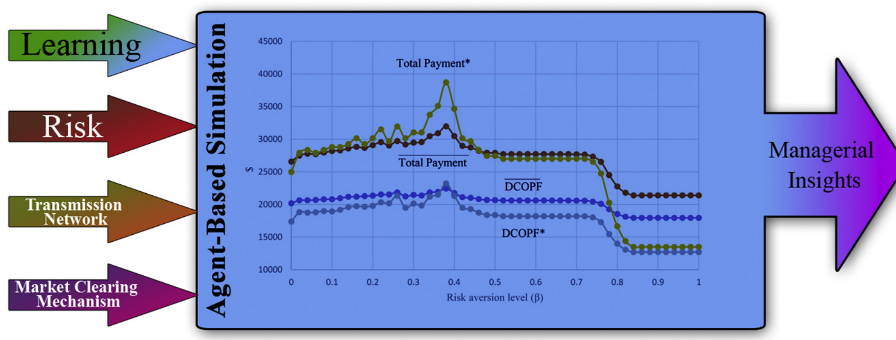
HIGHLIGHTS

- The first ABMS study to consider both learning and risk aversion of GenCos.
- Presenting an agent-based simulation of GenCos' behavior in electricity markets.
- Conducting a large-scale analysis with a wide range of learning model parameters.
- Analyzing effects of risk aversion on GenCos' bid prices, profits, and learning.
- Showing that some level of risk aversion can improve GenCos' profits.

GRAPHICAL ABSTRACT



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ABSTRACT

This paper studies the effects of learning and risk aversion on generation company (GenCo) bidding behavior in an oligopolistic electricity market. To this end, a flexible agent-based simulation model is developed in which GenCo agents bid prices in each period. Taking transmission grid constraints into account, the ISO solves a DC-OPF problem to determine locational prices and dispatch quantities. Our simulations show how, due to competition and learning, the change in the risk aversion level of even one GenCo can have a significant impact on all GenCo bids and profits. In particular, some level of risk aversion is observed to be beneficial to GenCos, whereas excessive risk aversion degrades profits by causing intense price competition. Our comprehensive study on the effects of *Q*-learning parameters finds the level of exploration to have a large impact on the outcome. The results of this paper can help GenCos develop bidding strategies that consider their rivals' as well as their own learning behavior and risk aversion levels. Likewise, the results can help regulators in designing market rules that take realistic GenCo behavior into account.

1. Introduction

In this work, we present a wholesale electricity market simulation with learning agents. The agents are power generation companies (GenCos) that engage in repetitive hourly pool trading. We are concerned with how the learning behavior and risk aversion of competing GenCos will shape GenCo bid prices and profit levels.

Electricity markets are oligopolies, and electricity demand is often considered inelastic in the short term with respect to price. In addition, transmission line constraints, and the relative locations of electricity demand and supply can provide market power to individual GenCos. Due to all these reasons, GenCos can bid above their marginal costs and obtain positive profit. This possibility, and the importance of the power sector for the economy has triggered a

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Nomenclature

Indices

i, k, l	GenCos or nodes
j	bids
t	simulation iterations

Sets

BR	set of transmission lines
B_i	set of available bids of GenCo-i
H_{ij}	history of all realized profits for submitting bid price alternative b_{ij}

Parameters

n	number of nodes in the network
P_i^{max}	the maximum generation capacity of GenCo-i (MW)
C_i	production cost of GenCo-i ($/MW h)
D_k	power demand at node-k (MW)
F_{kl}^{max}	thermal limit for real power flow on line kl
y_{kl}	negative of the susceptance value for line kl
β_i	risk aversion level of GenCo-i
α_{it}	recency rate of GenCo-i at iteration t
α_{i0}	initial recency rate of GenCo-i
ϵ_{it}	exploration parameter of GenCo-i at iteration t
ϵ_{i0}	initial exploration parameter of GenCo-i
max_t	number of iterations

Variables

Θ_i	voltage angle at node-i *(radians)*
LMP_i	locational marginal price at node-i ($/MW h)
P_i	power injected by GenCo-i (MW)
b_{ij}	jth bid price alternative of GenCo-i ($/MW h)
b_i	simplified notation for b_{ij} ($/MW h)
b_i^*	the best identified bid price of GenCo-i ($/MW h)
$\overline{b_i}$	average bid price submitted by GenCo-i over iterations ($/MW h)
r_{ij}	realized profit of GenCo-i for submitting b_{ij} ($)
r_i	simplified notation for r_{ij} ($)
r_i^*	profit of the best identified bid price of GenCo-i ($)
$\overline{r_i}$	average realized profit of GenCo-i over iterations ($)
Q_{ij}	Q-value of GenCo-i for submitting b_{ij} ($)
Q_{ij}^r	risk-modified Q-value ($)
$\overline{Q_i}$	average Q-value of GenCo-i over different scenarios ($)
CP_i	cumulative profit of GenCo-i ($)
$\overline{CP_i}$	average cumulative profit of GenCo-i over different scenarios ($)

wave of research into the strategic bidding behavior of GenCos (see, for example, [1–4]).

In this study, building on [5], we develop a flexible agent-based simulation model (ABMS) to characterize the evolution of a dynamic electricity market under transmission grid constraints. ABMS models have gained popularity in electricity market research because they offer advantages over game-theoretical models such as the ability to model heterogeneous players and observe the dynamic evolution of the market. The distinction of our ABMS model is that it considers both the *learning behavior* and *risk aversion* of GenCos.

In practice, GenCos often make bid decisions without proper information on the characteristics (such as capacity, cost, and/or financial situation) and bid history of competing GenCos. There is, however, also the potential for learning due to the repetitive nature of trading as GenCos interact with each other every day and gain experience. Due to learning and adaptation, GenCos can be expected to exhibit time-variant bidding policies. While learning individually, through its bids, each GenCo also has an impact on all the prices and dispatch quantities in the market. In this study, we are interested in observing how the collective learning of the GenCos will change the market. For example, will a GenCo discover its strategic advantage, such as low cost or a favorable position in the network, and learn over time to take advantage of it? We model GenCo learning using the Q-learning approach. In particular, we extend the learning model of [5,6] by considering time-dependent learning model parameters, similar to [7].

The literature that addresses GenCo behavior generally assumes risk-neutral decision makers whose objective is to maximize only the expected profit. In reality, however, GenCos may act risk-averse because they are exposed to increased levels of risk due to fluctuations in hourly prices and dispatched power quantities. To study the effects of risk aversion, we adopt a model in which risk is captured through the variance of past realized profits.

The major contributions of this paper can be summarized as follows: First, this is the first ABMS paper that studies the joint effects of learning behavior and risk aversion on GenCo bid prices and profits. Second, we present a flexible simulation model that can characterize the evolution of a dynamic electricity market under transmission constraints and time-dependent learning parameters. Third, we show that a certain level of risk aversion can improve GenCos' profits, whereas excessive risk aversion decreases profits due to intense price competition. Finally, we present a comprehensive study on the effects of Q-learning parameters, in which we find the level of exploration to have a large impact on results.

The remainder of the paper is organized as follows: In Section 2 we summarize the related literature. In Section 3, we present the model with risk-neutral GenCos, discussing the network and market structures as well as our learning model. In Section 4, we illustrate the learning model and simulation algorithm through two case studies. In Sections 5 and 6, we discuss the model with risk-averse GenCos and the related simulation study, respectively. Section 7 presents the simulation study regarding the effects of Q-learning parameters. Finally, we discuss the implications of our results in Section 8, and conclude in Section 9.

2. Literature survey

Ventosa et al. [8] provide a review of electricity market modeling approaches, classifying the literature into optimization, equilibrium and simulation models. Among these, game-theoretical models aim to characterize the equilibrium when players compete in quantity (Cournot competition [9]), in price (Bertrand competition [10]), or by submitting supply functions (supply function equilibrium [2,11]). There are also the more general conjectural variation type models [12–14].

Game-theoretical models have been extensively used because they offer insights into the strategic behavior of players and allow an easy derivation of equilibrium results. However, they are too stylized to reflect the realities of complex electricity markets [1]. Almost all game-theoretical models assume players to be rational, which often does not hold in practice, and implicitly assume GenCo behavior not to change over time. In addition, transmission grid constraints are ignored in most game-theoretic electricity market