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An agent-based simulation of power generation company behavior in electricity markets under different market-clearing mechanisms

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ABSTRACT

Deregulated electricity markets are expected to provide affordable electricity for consumers through promoting competition. Yet, the results do not always fulfill the expectations. The regulator's market-clearing mechanism is a strategic choice that may affect the level of competition in the market. We conceive of the market-clearing mechanism as composed of two components: pricing rules and rationing policies. We investigate the strategic behavior of power generation companies under different market-clearing mechanisms using an agent-based simulation model which integrates a game-theoretical understanding of the auction mechanism in the electricity market and generation companies' learning mechanism. Results of our simulation experiments are presented using various case studies representing different market settings. The market in simulations is observed to converge to a Nash equilibrium of the stage game or to a similar state under most parameter combinations. Compared to pay-as-bid pricing, bid prices are closer to marginal costs on average under uniform pricing while GenCos' total profit is also higher. The random rationing policy of the ISO turns out to be more successful in achieving lower bid prices and lower GenCo profits. In minimizing GenCos' total profit, a combination of pay-as-bid pricing rule and random rationing policy is observed to be the most promising.

1. Introduction

Deregulated electricity markets procure most of the electricity through several trading floors some of which are designed as auction-based markets. In most regional/national markets, these trading floors are controlled and governed by an Independent System Operator (ISO).

We focus on the day-ahead market in which Power Generation Companies (GenCos) compete for the next day supply of an inelastic load demand. In the day-ahead market's auction, for each hour of the following day, each GenCo bids the minimum acceptable unit price of electricity for itself. Based on the predetermined market-clearing mechanism, the ISO determines the market-clearing price and each GenCo's assigned power. We address two questions regarding the ISO's market-clearance mechanism that are at the heart of policy discussions on deregulated electricity markets: Which mechanisms lead to (1) more competitive price bidding by GenCos, (2) lower GenCo profits, meaning higher customer benefit.

The market clearing mechanism that we consider includes a pricing rule and a rationing policy. We compare the two most common pricing rules in the literature: Uniform and pay-as-bid (or, discriminatory) pricing (see Cramton, 2004). With uniform pricing, all GenCos with winning bids are paid the market-clearing price, whereas with pay-as-bid pricing, each GenCo is paid at its own bid price. In addition to uniform and pay-as-bid pricing, we also provide results under a DC-OPF rule under which, each region in the transmission grid may have a different electricity price due to physical constraints of the transmission lines.

By “rationing policy”, we refer to the way remaining demand at the market cleaning price is auctioned when multiple GenCos' bids coincide at that price. The rationing decision is part of real electricity market exchange mechanics (See, for example Madlener and Kaufmann, 2002), however it has not been addressed in electricity markets literature before.

Learning is an important aspect of electricity markets as GenCos engage in auctions repeatedly for every hour, and thus obtain experi-

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ence that can change their bidding behavior. To capture this dynamic, we develop an agent-based simulation model where GenCos can learn from their own experience based on a variant of the well-known Q-learning algorithm. Using this model, we simulate the repetitive auction process under different market clearing mechanisms in a number of case studies. We compare the results of our simulations with the Nash equilibrium predictions of static game-theoretic models.

This work contributes to both managerial and academic literature in a number of ways. Our results can guide ISOs and GenCo managers regarding the merits of different market clearance mechanisms. Comparisons between uniform and pay-as-bid pricing is definitely not new in the literature. However, we extend this comparison with the rationing policy dimension, and we provide results that incorporate the interplay between learning, dynamic competition, and ISO's clearance mechanism. In particular, we show that GenCo learning can take the market to a different direction than predicted by standard game-theoretical models. Finally, unlike most papers in literature, we present results for a wide range of learning model parameters.

The remainder of this article is organized as follows. In Section 2, we review relevant literature from three different perspectives. In Section 3, we present the market-clearing mechanism of the electricity market, explaining the pricing rules and rationing policies. The learning procedure and the simulation model are discussed in Section 4. Our game-theoretical understanding of the auction mechanism in electricity markets and the significance of Nash equilibrium are addressed in Section 5. Section 6 presents the results of simulation experiments and our findings.

2. Related work

We present the related literature in three parts: learning and game-theory, applications of agent-based simulation, and analysis of pricing rules.

2.1. Learning and game-theory

Due to repetitive nature of auctions in the electricity markets, GenCos are expected to learn by gathering new information in each repetition of the auction and improve their performance over time. In this respect, analyzing GenCos' behavior without a learning mechanism would lead to inaccurate results. Even in the early years of game-theory, researchers have been interested in learning models. Studying convergence to Nash equilibrium in the presence of learning has attracted a lot of attention from game-theory modelers as well as energy-economics community.

Aumann (1987) claims that Nash equilibrium concept is one of the most applied concepts in economics; yet, it is not crystal clear under what condition players might be expected to play a Nash equilibrium. Mailath (1998) discusses various justifications that have been advanced for equilibrium analysis and points out learning as the least problematic justification. Also, Mailath (1998) notes that convergence to Nash equilibria is a necessary condition in the evolutionary dynamics for any reasonable model of social learning when the number of players is large enough. Kalai and Lehrer (1993) show that under some simplifying assumptions, rational learning leads to Nash equilibrium.

Hart and Mas-Colell (2001b) propose "reinforcement" models in which all players can be led to an equilibrium of the stage game. Their learning procedure, unlike the "regret-matching" procedure (Hart and Mas-Colell, 2001a), does not need to observe all past payoffs, and players do not need to know their own payoff function. Wang and Sandholm (2002) state that even agents with non-conflicting interests may not be able to learn an optimal coordination policy in the presence of multiple Nash equilibria. As a solution, these authors propose a new learning mechanism based on reinforcement learning that converges to an optimal Nash equilibrium with probability one in any team Markov game.

2.2. Agent-based simulation of electricity markets

Although analytical models can be employed to study learning mechanisms, the expected outcomes of these models are not necessarily observed in practice due to strict simplifying assumptions (David and Wen, 2000). A widely accepted alternative tool is Agent-based Modeling and Simulation; it can provide better understanding of real-life markets especially when analytical models show poor tractability in investigating complicated problems. Li and Shi (2012) claim that agent-based modeling and simulation is a viable approach which provides realistic insights for the complex interactions among various market players.

Existence of multiple Nash equilibria can disrupt GenCos' learning process in such a way that the long-run equilibrium is not necessarily achieved. Krause et al. (2004) study a day-ahead market where GenCos learn by reinforcement learning (Q-learning). These authors' simulation does not converge in the existence of multiple Nash equilibria. The GenCos' strategies pendulate between those Nash equilibria. The oscillation between different Nash equilibria in the reinforcement learning process can be overcome by making better use of collected information. To this end, Wang (2009) used the SA-Q-learning algorithm with Metropolis criterion.

Naghibi-Sistani et al. (2006) apply Q-learning for agents' bidding in a pool-based power market with uniform pricing. They show that a participant with reinforcement learning capability could ultimately learn the optimal policy and could adapt himself to unknown parameters in the environment. The authors also find that under reinforcement learning, bids can converge and stay in the Nash equilibrium for a two-participant case. Nevertheless, these authors have not studied other pricing rules than uniform pricing and their impact on convergence.

We propose a modified version of the standard Q-learning algorithm. Different from the standard algorithm, ours is a state-independent one where Q-values are expressed as functions of actions only (Similar to Krause et al. (2004) and Krause and Andersson (2006)). In addition, it is similar to the Simulated Annealing (SA) Q-learning method (Guo et al., 2004) in that both methods employ a time-decaying exploration parameter. We use a linear decay, whereas the SA Q-Learning method uses a geometric function. The time decaying exploration parameter reflects the increasing experience of agents in the decision making process, and helps the algorithm achieve convergence. Table 1 presents main features of popular learning algorithms in order to facilitate a comparison with our method.

2.3. Pricing rules and rationing policy

Selecting a pricing rule is a vital decision for the ISO as it is likely to affect GenCos' strategic bidding behavior. Researchers have been investigating the characteristics of pricing rules to improve the functionality of underlying markets.

Kahn et al. (2001) argue that the proposed shift from uniform to pay-as-bid pricing in California Power Exchange was a mistake and contrary to expectations, it will not reduce electricity prices. Under uniform pricing, GenCos have an incentive to bid their true marginal generation cost (Oren, 2004) which will contribute to efficiency in power dispatch. Under pay-as-bid pricing, on the other hand, GenCos will bid at their expectation of the market clearing price. For that reason, bid prices are expected to be higher under pay-as-bid. However, this does not necessarily result in a higher market price for electricity under pay-as-bid pricing. This is because under uniform pricing, all GenCos are paid at the market clearing price, whereas under pay-as-bid, they are paid at their own bids which are generally lower than the market clearing price. Variation in bid prices and consequently the short-run volatility in market prices is expected to be lower under pay-as-bid than under uniform pricing (see, for example, Tierney et al., 2008 and Mount, 2001). That is, pay-as-bid pricing will result in a flatter supply function.