Non-cooperative game-theoretic model of demand response aggregator competition for selling stored energy in storage devices

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HIGHLIGHTS

- Proposing a game-theoretic market model for selling stored energy in batteries.
- Calculating aggregators' payoffs in various non-cooperative games.
- Analysis the impact of demand response scheduling on aggregators' payoff.
- Finding the optimal bidding strategies for the aggregators in the market model.
- Obtaining the Nash equilibrium in an incomplete information game.

ARTICLE INFO

ABSTRACT

Our research is primarily concerned with the construction of a theoretical model of the competition between demand response aggregators for selling energy previously stored in an aggregation of storage devices (which the aggregator manages) given sufficient demand from other aggregators through an incomplete information game. The model culminates in a game-theoretically justifiable decision making procedure for the sellers which may be used to predict and analyze the bids made for energy sale in the market. The methodology for applying the model is worked out in detail for a three-aggregator case where two players compete with each other for sale to a third. Relevant numerical data for the competition is taken from a real case study which took place on the island of Maui, Hawaii. This market framework is presented as an alternative to the traditional vertically-integrated market structure, which may be better suited for developing demand response and smart grid technologies. We consider two non-cooperative game variants with different market conditions: one competition with no limitation, and one a Stackelberg competition subject to limitations on transaction price and size, each separately with and without inclusion of demand response scheduling (we focus on significant load-bearing thermostatic storage devices such as water heaters, though the principles should be applied generally). Determining the optimal bidding strategies follow the same procedure, and the equilibrium bidding strategies of all others are determined by each player in each case and demonstrates the wide applicability of our methods in each case. Bidding strategy is dependent on parameters inherent to an aggregator's energy storage hardware. Demand response scheduling offers greater payoff for aggregators who implement it, compared with those who do not. Addition of transaction price and power quantity regulations to the market lowers payoffs for all aggregators participating in the market relative to competition with no limitation.

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1. Introduction

Development of smart grid technologies offers substantial advantages (for all parties involved) over traditional vertically integrated electric utilities [1–3]. Demand side management (DSM) programs have been developed to use the available energy resources more efficiently without installing new generation and transmission infrastructure. In many of the deployed DSM programs (e.g., in [4–6]), the main focus has been on interactions between the utility company and end users. Due to the recent advancements in smart grid technologies especially in terms of two-directional communication between utility and end users [7–9], the interactions between users do not have to be manual, but can be automatic through two-way digital communication. In

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Nomenclature

C_h^{bat}	discharging cost of battery in house h
ΔE_h	discharging energy of battery in house h
ΔP_h	discarding power of battery in house h
t	time interval for updating load data
C_h^{grid}	charging cost of battery in house h
$C_h^{C\&M}$	capital/maintenance costs of battery
C_i	cost function of aggregator i
P_i	aggregated stored power in aggregator i
(a_i, B)	coefficients of cost function (players' types)
λ_i	marginal cost of aggregator i
λ_{0i}	marginal cost of electricity at P_{0i}
m_i	slope of bid curve (players' strategies)
R_i	payoff of player i
φ	spot market price
T_i	transaction power for aggregator i
R_{seller}	seller aggregator's payoff

R_{buyer}	buyer aggregator's payoff
t_A^m, t_B^n	types m and n in players A and B
π_{mn}	probability distribution of A's type m and B's type n
ε_S	players' strategy
EP_A^m, EP_B^n	expected payoffs of players A and B
$\eta_A^m(n), \eta_B^n(m)$	conditional probabilities of players A and B
H_A^m, H_B^n	conditional payoffs of players A and B
s_A^m, s_B^n	strategies of players A and B
Ψ_A^f, Ψ_B^f	probability distributions of players in scenario f
WH_{off}, WH_{on}	on/off status of water heaters
$elec_{ch}, elec_{exp}$	price status of grid electricity (cheap, expensive)
φ_T	transaction price
P_A, P_B	stored power in aggregators A and B for selling
L_C	power purchased by aggregator C

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this paper, a market framework has been developed based on game-theoretical concepts where Demand Response Aggregators (DRAs) compete with each other to sell energy stored in consumers' storage devices. Our model determines the optimal bidding decision for each DRA to maximize its own payoff despite incomplete information in the game and significant variations in prevalent market conditions.

Game theory has been used in power system markets to interpret a participant's behavior in deregulated environments and to allocate costs among pool participants [10]. Two different hybrid algorithms were presented in [11,12] for the Generation Expansion Planning (GEP) problem for a pool-based electric market where the modified-game-theoretic algorithms were divided into two programing levels: master and slave. A static computational game theoretic model has also been developed in [13] to investigate the impacts of competition on the wholesale price of electricity, the demand for electricity, the profits of firms, and levels of various polluting emissions. The most common electricity bidding mechanisms in electricity auction markets were analyzed using signaling game theory [14] and also a Swarm platform was used to develop a simulation model based for multiple agents. The role of sustainable energy volatility was investigated in the context of market participant's competitive expansion planning problem in [15]. An incomplete information non-cooperative game-theoretic method where each generation company (GENCO) perceives strategies of other market participants was applied to make decisions about strategic generation capacity expansion. A practical program was proposed in [16] for charging scheduling of plug-in hybrid electric vehicles based on game theory, aiming at optimizing customers charging cost. In another research work, a game approach was presented in [17] to formulate the charging problem of plug-in hybrid electric vehicles to jointly optimize the cost of the utility company and payoff of the customers. There are other applications of game theory in literature for energy and power markets. For instance, developing a dynamic game-theoretic model in [18] in natural gas and electricity markets, prospering a next-generation retail electricity market in [19] with high penetration of distributed residential electricity suppliers, and presenting a game-theoretic framework in [20] for economic operations of future residential distribution systems.

Game theory is an appropriate mathematical tool to solve many of the problems in DSM [21]. Several game-theoretical demand response (DR) programs have been proposed with different objectives such as: determining the optimal hourly incentive to be offered to customers who sign up for load curtailment [22,23], managing the demand in smart energy hubs [21,24,25], adjusting demand to meet supply, as well as smoothing the aggregated load in the system [26], and evaluating the impact of the response capability of smart-home consumers on promoting further distributed PV penetration [27]. An optimal time-of-use pricing with an evolutionary game-theoretic perspective was proposed in [28] for urban gas markets where a power structure DR program was employed to simulate user demand response. An energy management technique was proposed in [29] for electricity and natural gas networks based on integrated DSM which hubs were formulated as a non-cooperative game. Game theory has also been used to improve strategies of Decision-making (DM) in energy markets [30,31]. Basically, Game theory is the formal study of DM under competitive conditions where choices potentially affect the interests of the other players [32–34]. For example, a game theoretic modeling approach was performed in [35] to develop financial transmission rights bidding strategies for power suppliers assuming that they have adequately forecast locational marginal prices. The game theoretic model considered multiple participants as well as network contingencies. In another work, an evolutionary imperfect-information game approach was proposed in [36] to analyze bidding strategies in electricity markets with price-elastic demand. The research work presented in [37] characterized the impact of long-term plans on short-term maintenance decisions of GENCOs by applying the Cournot model, which has been used for strategic generation dispatch of generating units in electricity markets. Authors of [38] studied electricity users' long-term load scheduling problem and modeled the changes of the price information and load demand as a Markov decision process. Markov perfect equilibrium of a fully observable stochastic game with incomplete information was used in [38] to approximate the users' optimal scheduling policy.

Different types of games have been utilized for analysis of different types of problems in energy and power market. Games' types are categorized by number of players involved, symmetry of the game, and whether or not, cooperation among players is allowed. In the literature for power markets, the different game models used include: cooperative [39–42], non-cooperative [27,43–45], Stackelberg [46–48], multi-leader-follower [46], Forchheimer (one leader) [49], and Bertrand games (all players are leaders) [49]. Beside the these application, game theory has been used in diverse, and other related fields such as: analysis of Electric Vehicle (EV) charging station construction [50], charging method