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The role of energy storage in mitigating ramping inefficiencies caused by variable renewable generation

Ali Shahmohammadi[a], Ramteen Sioshansi[b,*], Antonio J. Conejo[b,c], Saeed Afsharnia[a]

[a] School of Electrical and Computer Engineering, University of Tehran, Tehran 11365-4563, Iran
[b] Department of Integrated Systems Engineering, The Ohio State University, 1971 Neil Avenue, Columbus, OH 43210, United States
[c] Department of Electrical and Computer Engineering, The Ohio State University, 2015 Neil Avenue, Columbus, OH 43210, United States

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ABSTRACT

Rising penetrations of variable renewable generation in electric power systems can raise operational challenges. One is that renewables can increase the need for dispatchable generation with fast-ramping capabilities. This can be costly, because in many instances flexible generators can be more expensive than baseload units that have slower ramping capabilities. If ramping capacity is not available, renewable curtailment may be needed. An alternate solution to this need for ramping is to use energy storage.

A question that this raises is how renewable and conventional generators and energy storage would interact in a market environment, and whether certain asset-ownership structures would result in more efficient co-ordination. To this end, this paper presents a multi-period market-equilibrium model of interactions between these different types of market agents. The impacts on renewable integration of conventional generators having limited ramping capabilities are studied through an illustrative case study. We also examine a variety of structures for the participation of energy storage in the market. We find that co-ownership and co-operation of renewable generators and energy storage brings about the best results from the perspective of alleviating market inefficiencies. Having energy storage directly controlled by the market operator or participating as an independent profit-maximizing firm is less efficient.

1. Introduction

The rising penetration of variable renewable generation sources is putting operational strains on electric power systems. As one example, there is a growing need for flexible dispatchable generation with fast-ramping capabilities to accommodate the variable and uncertain nature of real-time renewable-energy availability. Otherwise, renewable generation may be curtailed. This can be a costly proposition, however, because flexible generation units may have higher operating costs than less-flexible baseload units.

The literature studies numerous ways of mitigating the cost of ramping needs imposed by renewable generators. Three commonly studied approaches are to better predict and manage the cost of generator ramping needs [1–4], use demand response to engender demand-side flexibility [5–7], or use energy storage to meet ramping needs [8–13].

Analyses of the first approach includes the work of Kubik et al. [2], which examines the benefits of steps, such as fuel switching in conventional generators, to improve a power system's ramping capabilities and accommodate more renewable generation. Edmunds et al. [3] investigate the critical and growing role of natural gas-fired generation units in providing ramping capability to the British power system with increasing variable renewable generation. Zha et al. [4] propose a new approach to predicting the ramping needs of wind generation.

Studies of demand response include the work of Heydarian-Forushani et al. [5], which presents a stochastic network-constrained unit commitment model with demand response. Their model schedules both generating units and responsive loads in systems with high wind penetrations. Salpakari et al. [6] study the optimal control of electric heating systems as a source of flexible demand for renewable integration. Alahaivala et al. [7] also study flexible heating loads for wind integration and ramp mitigation. Their work suggests that heating loads could be utilized to reduce ramp rates, wind curtailment, and operational costs associated with severe ramps in wind availability.

Energy storage is a third option for increasing a power system's flexibility and ramping capability. There do remain, however, some challenges in adopting energy storage and in accommodating them within existing market designs. This reality has attracted studies focusing on the conflict between the technical benefits and the economic challenges in compensating energy storage for their services under

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* Corresponding author.
E-mail addresses: A.shmohamadi@ut.ac.ir (A. Shahmohammadi), sioshansi.1@osu.edu (R. Sioshansi), conejonavarro.1@osu.edu (A.J. Conejo), safshar@ut.ac.ir (S. Afsharnia).

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current market designs [8,14–16]. Despite this issue, a number of works examine the benefits of energy storage in accommodating renewables. O'Dwyer and Flynn [10] use a sub-hourly analysis to explore the role of energy storage in reducing operating costs and enhancing system efficiency and flexibility with high renewable penetrations. Khodayar et al. [11] propose an approach to determine the multi-period ramping capabilities of dispatchable generation resources. They further integrate energy storage to serve the ramping requirements imposed in the day-ahead electricity market by renewable generators. Heydarian-Forushani et al. [9] develop a robust optimization framework to optimize unit commitment decisions in systems with high penetrations of wind power. Their model incorporates demand response and bulk energy storage in co-optimized energy and reserve markets. Safaei et al. [17] introduce a novel compressed-air energy storage (CAES) system, wherein the waste heat of compression is reused for different heating demands through distributed compressors. They also compare the economics of their proposed distributed CAES to a traditional CAES system in a restructured electricity market, in which storage co-operates with wind generators. This co-operation allows the joint wind and CAES plants to participate like conventional dispatchable generators [18]. Hittinger et al. [19] propose a model in which a gas turbine, a wind generator, and fast-ramping energy storage are co-located and co-operating with each other to provide near-constant baseload power. Their proposed model is mostly suitable for isolated grids, due to the high energy-supply cost of their proposed hybrid energy system. Their method allows using significant amounts of wind generation, while reducing supply fluctuations to a small deadband.

These works leave some unanswered questions regarding the role of energy storage in mitigating ramping-related challenges surrounding renewable integration. The first are the potential interactions between strategic profit-maximizing behavior by renewable or conventional generators and supply-side flexibility. The second is the role of energy storage in mitigating flexibility issues. The third is the effect of market and asset-ownership structure on market efficiency and the ability of energy storage to mitigate ramping and flexibility issues. Answers to these questions would allow policy makers, market designers, and regulators to change market rules and structures to more efficiently accommodate high penetrations of renewable energy into electric power systems.

To this end, this paper presents a bi-level multi-period model of a spot-market equilibrium, which includes conventional and renewable generators and energy storage. The lower level of the problem represents the spot market being cleared by a market operator (MO). The MO's problem includes ramping constraints, which reflect generator flexibility. The upper level of the problem represents the decisions of the profit-maximizing generator and energy-storage firms in offering capacity to the market. The resulting bi-level problem is solved by first replacing the lower-level problem with its necessary and sufficient primal-dual optimality conditions. This gives a mathematical program with equilibrium constraints (MPEC) for each profit-maximizing firm. An equilibrium program with equilibrium constraints (EPEC) is obtained by combining all of the firms' MPECs. We employ a series of linearization techniques to recast the EPEC as a mixed-integer linear program (MILP). Solving this MILP gives candidate solutions that may be market equilibria. We use a diagonalization technique to determine which EPEC solutions are market equilibria, which are closely analyzed.

We demonstrate the proposed model using an illustrative case study. The case study also allows us to examine market interactions between conventional and renewable generators and energy storage under different asset-ownership and market structures. Specifically, we examine cases in which different firms behave as price-makers or price-takers. A price-taking firm is one that does not account for the impact of its offering behavior on market prices and dispatch levels. Thus, a price taker behaves competitively. A price-making firm, conversely, does take into account the impacts of its offers on market prices and dispatch. Thus, a price maker may opt to offer its generation strategically at a price that differs from marginal cost to impact its sales of energy or the price at which it is paid. We show that with strategic price-making firms, a market structure in which renewable generation and energy storage are co-owned is the most efficient in terms of accommodating renewable energy. Conversely, having energy storage directly controlled by the MO or participating as an independent profit-maximizing firm is less efficient.

This paper makes a number of contributions to the existing literature. First, we develop a multi-period bi-level market equilibrium model that can fully capture generator-ramping constraints and energy storage. Second, we convert the bi-level problem into an EPEC and recast it as an MILP, which can be tractably solved. Finally, we demonstrate the value of our model in being able to examine market interactions between conventional and renewable generation and energy storage under different market and asset-ownership structures. Our model can also examine different strategic behavior on the part of the participating firms.

The remainder of this paper is organized as follows. Section 2 provides more background on market-equilibrium, MPEC, and EPEC modeling. Section 3 provides an overview of our bi-level model. The appendices provide details on the steps that are taken to convert the bi-level model into a tractable MILP. Section 4 introduces our numerical case study and Section 5 summarizes our case study results. Section 6 concludes.

2. Market-equilibrium, MPEC, and EPEC modeling

This paper takes a complementarity-based approach to study market interactions between conventional and renewable generation and energy storage. Complementarity models are a powerful tool for modeling market interactions. The power of complementarity modeling lays in its ability to model the simultaneous optimization of multiple firms competing in a market [20]. In doing so, complementarity models allow computing market equilibria. For instance, Virasjoki et al. [12] use a Nash-Cournot model to analyze the effects of energy storage on ramping cost and congestion in a power system with renewable generators. Their analysis concludes that in a perfectly competitive market, energy storage helps to reduce congestion and ramping costs while potentially increasing greenhouse gas emissions from conventional generators. Conversely, they find that energy storage is less effective in mitigating congestion and ramping constraints in a market in which firms behave strategically. On the other hand, energy storage does not have the same negative impact on greenhouse gas emissions in a strategic setting.

An MPEC is an extension of a simple complementarity model that contains complementarity conditions in its constraint set. As such, an MPEC can represent more complex market interactions than a simple complementarity model can. Nasrolahpour et al. [13] propose an MPEC to make optimal operating decisions of price-making energy storage in a market. Their model considers uncertain output from wind generators and conventional generators that have limited ramping capabilities. Wang et al. [21] also employ an MPEC for optimizing the offering strategy of a merchant energy storage firm. Their analysis considers a ramp-constrained power system with high penetrations of renewable energy. Their model includes an additional day beyond the operating period being optimized, which attaches carryover value to energy stored at the end of the day [22,23]. Because MPECs can model leader-follower games with only a single leader, the analyses of Nasrolahpour et al. [13] Wang et al. [21] assume that *only* energy storage behaves as a strategic profit-maximizer.

EPECs are a further and more complex extension of MPECs that are able to model leader-follower games with multiple leaders that are simultaneously behaving strategically (*e.g.*, maximizing profit). For example, Yaghooti et al. [24] use an EPEC to analyze the impacts of ramping limits on the strategic profit-maximizing behavior of multiple