Market equilibria and interactions between strategic generation, wind, and storage

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HIGHLIGHTS

- Develop multi-period equilibrium model with conventional, wind, and storage units.
- Study equilibrium behavior within a price/quantity-based offer framework.
- Apply models to an illustrative case study, showing profit and social welfare benefits of energy storage.
- Sensitivity analysis shows robustness of qualitative observations.
- Demonstrate energy storage could recover much of its investment cost on the basis of this use.

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ABSTRACT

Rising wind penetrations can suppress wholesale energy prices by displacing higher-cost conventional generation from the merit order. Wind suffers disproportionately from this price suppression, because the price is most suppressed when wind availability is high, hindering wind-investment incentives. One way to mitigate this price suppression is by wind exercising market power, which introduces efficiency losses. An alternative is to use energy storage, which allows energy to be stored when wind availability is high. This stored energy is later discharged when wind availability is lower and prices are higher.

This paper proposes a bilevel equilibrium model to study market equilibrium interactions between energy storage and wind and conventional generators. We represent the market interaction using an equilibrium problem with equilibrium constraints. An illustrative case study is used to demonstrate the social welfare and profit benefits of using energy storage in this manner.

1. Introduction

The electricity industry has seen rising penetrations of non-dispatchable renewable generation. This has historically been driven by policy mandates, such as subsidies or renewable portfolio standards [1–3]. These mandates have resulted in renewable cost reductions, through learning-by-doing and economy-of-scale effects, to the point that some renewables are becoming prudent investments without the mandates [3–5].

Green and Vasilakos [6] study the market impacts of high renewable penetrations. They demonstrate that as its penetration increases, wind has the effect of suppressing wholesale energy prices by displacing higher-priced generation from the merit order. Wind suffers disproportionately (compared to conventional generation) from this price

suppression, because the price-suppression is greatest during periods that wind availability is high. Thus, this price suppression can disproportionately reduce wind-investment incentives. Buygi et al. [7] further demonstrate that this price-suppression effect can also be attributed to the assumption that renewable generators are small players that behave nonstrategically, meaning that their generation unduly suppresses energy prices.

Wind could mitigate this price suppression by exercising market power [8]. This involves wind generators offering their supply into the market above cost. This solution typically introduces efficiency losses, however. Efficiency losses arise because wind generators are withholding supply, allowing higher-cost generation that would otherwise (absent the exercise of market power) not clear the market to set the price.

An alternate solution to the price-suppression effect is to use energy storage [9]. Energy is stored when high wind availability would otherwise suppress prices and is later discharged when wind availability is lower and prices are higher. Wind derives this benefit from energy storage regardless of whether it owns the storage or not [9]. Previous market analyses of wind and storage are limited, however, because they often rely on highly stylized models to find an equilibrium between storage, wind, and conventional units. This paper relaxes those restrictive assumptions and examines the market interactions between storage, wind, and conventional units under a variety of market and ownership structures within a bilevel-equilibrium framework.

At a high level, the model that we propose assumes that there is a set of firms, each of which can own some combination of storage, conventional, and wind units. The firms make offers, which consist of price/quantity pairs specifying the price at which storage is willing to be charged or discharged or the price at which generation is willing to supply energy, to a centrally dispatched market. The bilevel nature of the model arises because there is a lower-level problem embedded within the firms' profit-maximization problems representing the clearing of the market (on the basis of the firms' offers). An equilibrium framework arises because the firms simultaneously determine their offers into the market to maximize profits.

Thus, unlike previous analyses, the modeling framework that we propose allows for a great deal of flexibility in modeling interactions between storage, conventional, and wind units within a market environment. Our modeling framework is somewhat simplified compared to other analyses of renewable energy and storage technologies [10–13] in terms of representing engineering details. Other works may model more complex technical characteristics of the technologies in question, but neglect market equilibria. The model that we propose fills this gap, which is important insomuch as how conventional, wind, and storage units interact within a market environment raises important policy and market-design issues. Many other works, conversely, examine storage or renewables from the perspective of a central planner. The model that we propose provides a reasonable balance between engineering fidelity, representation of market interactions, and model tractability.

We use optimality conditions of the lower-level problem to convert the bilevel profit-maximization problem of each firm into a mathematical program with equilibrium constraints (MPEC). We then convert the collection of MPECs into an equilibrium problem with equilibrium constraints (EPEC), which we solve to find Nash equilibria.

We apply our modeling framework to an illustrative case study with a number of market and asset-ownership structures. This includes cases in which energy storage and wind are price-taking or price-making and we find equilibria ranging from extremely collusive to competitive outcomes. We find the same price-suppression effect that Green and Vasilakos [6] and Buygi et al. [7] do and demonstrate the efficiency losses of having the wind generator exercise market power. Our results show that energy storage is a preferred solution to the price-suppression effect from the perspective of social welfare and wind- and conventional-generator profits.

The remainder of this paper is organized as follows. Section 2 provides a survey of literature that is related to our work and summarizes the major contributions of our work relative to this literature. Section 3 details our modeling framework and the derivation of the market-equilibrium problem. Sections 4 and 5 provide our case-study data and results, respectively. Section 6 summarizes the results of three sensitivity analyses, in which conventional-generator costs and ramping capabilities and wind availability are varied. Section 7 concludes.

2. Related literature and our contributions

A variety of techniques are used in the literature to model the offering and bidding strategies of players participating in energy markets. Complementarity models are recognized as being a particularly powerful tool to represent such games. This is because complementarity models are able to model the simultaneous optimization of firms competing in a market [14]. Zou et al. [15] examine the benefits of energy storage in supporting renewable generation in joint energy and ancillary service markets while Hu et al. [16] analyze the impact of demand response in an energy market with demand uncertainty. Both of these works take a complementarity approach to finding Nash-Cournot equilibria. Zou et al. [17] employ a complementarity model of a multi-period Nash-Cournot equilibrium to study the evolution of the current Chinese power system to a renewable-dominated design in the future.

MPECs are an extension of the complementarity model that can represent more even more complex market interactions. MPECs can be used to represent sequential market interactions and leader/follower games. This is because the optimization problem of the first player or leader in the game can have embedded within it equilibrium constraints that characterize the optimal decisions of the second player or follower. Thus, this framework captures the first player or leader making decisions that take into account the optimal decisions that are subsequently made. Zhang et al. [18,19] use an MPEC model to optimize the trading strategies of a distribution company with distributed energy resources and with demand-responsive customers, respectively.

An EPEC model further extends the MPEC by having multiple leaders as opposed to only one. Thus, an EPEC can be thought of as consisting of one MPEC for each leader, with variables in the different MPECs being interrelated to one another (because the leaders are all participating in the same equilibrium) [14]. One of the complications of EPECs is that they are often highly non-convex problems. Thus, it can be very challenging to find all possible equilibria. In practice, this issue is overcome by using different objective functions in the overall EPEC problem, which can provide a bounding range of equilibria. For instance, one could solve EPECs with welfare-maximization and generator profit-maximization as the objective functions, which provides a range of most- and least-competitive equilibria. Kazempour and Zareipour [20] use an EPEC model to analyze the impacts of large strategic wind producers in day-ahead and real-time markets. However, they solely use profit-maximization of the generators as the objective function of the EPEC, meaning that they examine only the least-competitive market equilibria. Dai and Qiao [21] employ an EPEC model to obtain equilibria in a market with both strategic and nonstrategic wind generators. They find the same price suppression effect that Green and Vasilakos [6] and Buygi et al. [7] do and that higher renewable penetrations decrease prices. They also observe transmission congestion potentially increasing prices.

Although EPEC models are used to study market equilibria with renewables, interactions between renewables and energy storage are not well studied in the literature. This is particularly true of analyses of interactions between renewables and storage within a market equilibrium. This is because modeling energy storage requires a multi-period model to capture intertemporal constraints related to energy storage. Zou et al. [22] develop an equilibrium model to study the market impact of strategic storage firms. However, their treatment of the market equilibrium is not as comprehensive as ours. Furthermore, their modeling approach requires the solution of a nonconvex nonlinear optimization problem, which can create computational issues. Our approach, conversely, uses mixed-integer linear programs (MILPs), which are not prone to the same computational challenges. Their study is focused on comparing strategic behavior of different energy storage systems. Our work examines market interactions between storage and renewables.

Given this state of the literature related to market interactions between energy storage and renewables, our work makes four main contributions in this topic area. First, we develop a novel multi-period equilibrium model that comprehensively captures generator and storage offers in the form of price/quantity blocks. The goal of developing this model is to analyze the price-suppressing effect of renewables and investigating possible means of mitigating it. At the same time, the model framework that we develop relaxes many of the restrictive