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When energy storage reduces social welfare

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ABSTRACT

This paper examines the potential welfare effects of storage under different market structures. This includes combinations of perfectly competitive and strategic generation and storage sectors, and standalone and generator-owned storage. We demonstrate that if the generation sector is perfectly competitive and does not own storage, then storage cannot be welfare-diminishing. Otherwise, generator-owned storage or standalone storage in a market with strategic generating firms can reduce welfare compared to the no-storage case. This contradicts conventional wisdom that adding firms to an imperfectly competitive market typically reduces welfare losses.

1. Introduction

Recent developments in the electricity industry have increased interest in energy storage. This includes the introduction of markets that provide prices that signal the value of many of the services that storage can provide, and the ability of storage to ease the integration of renewables into power systems. EPRI (1976) provides an early discussion of storage technologies and their relative performance. Since it is framed by the 1970s, before the introduction of restructured electricity markets, it focuses on storage use by a vertically integrated utility to replace peaking generation capacity. More recent works, including those of EPRI-DOE (2003); Eyer et al. (2004); Eyer and Corey (2010); Denholm et al. (2010), recognize and discuss the broader array of services that storage can provide. This includes generation, transmission, and distribution capacity deferral, ancillary services, ramping, renewable curtailment, and end-user applications.

These discussions of potential storage uses are also supplemented by empirical and other analyses attempting to value these services. One of the most studied storage applications is energy arbitrage—charging storage when energy prices are low and discharging when prices are high. A number of works, including those of Graves et al. (1999); Figueiredo et al. (2006); Sioshansi et al. (2009, 2011), use historical price data and optimization models to estimate the value of storage. Walawalkar et al. (2007) estimate arbitrage value using historical price duration curves. These works find arbitrage values ranging between \$29/kW-year and \$240/kW-year in the markets examined, with the differences mainly stemming from the mix of generators that are marginal on- and off-peak. These analyses implicitly assume that the storage plant is sufficiently small compared to the market that its charging and discharging decisions do not affect prices. Sioshansi et al. (2009) explore the effects of relaxing this assumption, showing that arbitrage values diminish if prices respond to storage use. This is because off-peak prices rise and on-peak prices fall when storage is used, since it results in greater off-peak and less on-peak generation.

Other works expand on these by examining the effects of storage in a setting with responsive prices, from both a private value and social welfare standpoint. Sioshansi (2010) uses a stylized model, in which the generation sector is perfectly competitive, to explore the effects of ownership on storage use and welfare. He shows that regardless of who owns it (generator-, load-, and standalone-ownership cases are examined), storage is used in a suboptimal manner, insomuch as the welfare gains are less than what a social planner would achieve. Moreover, in some cases the addition of storage can reduce social welfare compared to the no-storage case. Sioshansi (2011) uses a case study, based on the Texas system, to examine storage and wind together in a market in which generators compete *a la* the supply function equilibrium model proposed by Klemperer and Meyer (1989). His work is motivated by the fact that wind can suppress energy prices by displacing high-cost generation. This price suppression can reduce wind profits and investment incentives since the effect is concentrated during hours with high wind availability. He demonstrates that storage can

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increase the selling price of wind, by charging storage when wind unduly suppresses prices and discharging during hours with lower wind availability. He also shows that this use of storage results in social welfare losses, compared to not having storage in the market. Schill and Kemfert (2011) examine the profit and welfare effects of storage in the German electricity market. Using actual market data, they consider cases with generator-owned and standalone storage, assuming that the players follow Nash–Cournot equilibria. They also find cases in which storage reduces social welfare compared to a no-storage case.

The cases in which storage reduces social welfare can be unexpected, insomuch as adding firms to an imperfectly competitive market typically improves allocative efficiency. Moreover, these findings are different from those of Sioshansi et al. (2009) who also examine storage use with responsive prices, but do not find welfare losses. This raises the question of what role market structure plays in these welfare losses, since these analyses study storage under different settings. Sioshansi et al. (2009) and Sioshansi (2010) assume perfectly competitive generation, whereas Sioshansi (2011) and Schill and Kemfert (2011) assume strategic behavior. The latter two analyses differ, however, in the specifics of the market structure considered. Sioshansi (2011) studies a high-wind case, in which strategic conventional generators compete in supply functions and strategic storage competes in quantities. Schill and Kemfert (2011), on the other hand, use the existing generator fleet with relatively little wind and assume that strategic conventional generators and strategic storage compete in quantities. Sioshansi (2011) further assumes storage to be standalone or owned by wind generators, whereas Schill and Kemfert (2011) study storage owned by conventional generators. Understanding what types of market and asset-ownership structures can potentially result in welfare losses is important and can help guide important policy decisions given today's storage renaissance.

The aim of this paper is to study these issues more methodically. We use a stylized model to examine what market and ownership structures can lead to storage having welfare-diminishing effects. We consider cases with different combinations of perfect competition or strategic behavior in the generation and storage sectors, and generator-owned and standalone storage, and arrive at four main findings. First, if the generation sector is perfectly competitive, standalone storage that is not owned by generators cannot be welfare-diminishing. However, strategic storage delivers less welfare benefits than perfectly competitive storage under such a market structure. Second, if generators behave strategically with respect to their production decisions, then storage can be welfare-diminishing. Under such conditions, perfectly competitive storage delivers greater welfare losses than strategic storage. Third, if storage is owned by a monopolist generating firm that makes perfectly competitive generation but strategic storage decisions, there can be welfare losses. If there are, instead, multiple symmetric storage-owning generators that make perfectly competitive generation but strategic storage decisions, the addition of storage cannot give welfare losses. Finally, we show that storage owned by generating firms making strategic generation and storage decisions can lead to welfare losses with any number of firms.

The case of generating firms that make perfectly competitive generation but strategic storage decisions can appear unrealistic. This structure could arise in some markets, however. For instance, the California ISO places restrictions, based on tested heat rates, on the offers of conventional generators in its wholesale markets. Hydroelectric generators, which have a storage capability insomuch as water can be withheld in one period to be used in another, are not subjected to such restrictions due to complex watershed constraints on their operations. This could give rise to the final set of cases that we examine.

The remainder of this paper is organized as follows. Section 2 details our generation and storage model and the various cases that we consider. Section 3 studies cases with perfectly competitive generation while Section 4 studies strategic generator cases with standalone (non generation-owned) storage. Section 5 considers cases of generator-owned storage and Section 6 concludes.

2. Basic model

We study interactions between generation and storage and their effects on prices and welfare using a two-period model. The two periods modeled represent off- and on-peak periods. Demand is assumed to be price-responsive, with period-t demand given by:

$$D_t(p_t) = N_t - \gamma_t p_t,$$

where D_t is measured in MW and p_t in \$/MW. We assume N_t, $\gamma_t > 0$, implying that demand is strictly decreasing in price but positive for some range of prices. We use the convention that period $t = 1$ is the off-peak period and $t = 2$ on-peak. Thus, we assume that:

$$D_2(p) \geq D_1(p), \forall\ p \text{ such that } D_1(p) \geq 0.$$

These functions can also be inverted, giving the inverse demand functions:

$$P_t(d_t) = \frac{N_t - d_t}{\gamma_t}.$$

We study storage use under two generation market structures. One assumes a perfectly competitive generation market, while the other assumes strategic generators that follow Nash–Cournot equilibria. We assume that the same generator fleet, with the same cost, is available in both the off- and on-peak periods. The total per-period generation cost of the fleet in the perfectly competitive case is given by:

$$c(g_t) = b \cdot g_t + \frac{1}{2} c \cdot g_t^2,$$

where $b, c \geq 0$ and g_t and cost are measured in MW and dollars, respectively. We further assume that:

$$P_t(0) > c'(0), \forall\ t,$$

or that there are always some strictly positive gains from trade. The per-period marginal generation cost is given by:

$$c'(g_t) = b + c \cdot g_t.$$

Inverting the marginal cost function gives the perfectly competitive supply function:

$$s(p_t) = \frac{p_t - b}{c}.$$

The strategic generation cases assume that the generation fleet is divided between G symmetric firms, each of which has a per-period operating cost of:

$$\hat{c}(g_t) = \hat{b} \cdot g_t + \frac{1}{2} \hat{c} \cdot g_t^2.$$

This implies that each firm has a per-period marginal generation cost of:

$$\hat{c}'(g_t) = \hat{b} + \hat{c} \cdot g_t.$$

Each generator's perfectly competitive supply function is found by inverting these marginal cost functions, giving:

$$\hat{s}(p_t) = \frac{p_t - \hat{b}}{\hat{c}},$$