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SOME POLICY AND RESEARCH QUESTIONS RELATED TO ENERGY STORAGE

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Abstract

This paper provides a survey of the history and future of storage development in the US and policy and analytical questions relating to storage. The paper discusses the history of storage development in the US, and some of the limitations in how storage investment was justified beginning in the 1970s, when much of the US's current storage capacity was built. Then we discuss potential uses of storage beyond serving as an alternative to peaking capacity and uses of storage by entities other than a traditional vertically-integrated utility. After we lay out some policy and research questions related to energy storage and show how questions such as regulation, market products, and ownership can greatly affect the true value of storage and incentives for and efficiency of storage use and investment.

Keywords

Energy storage, electricity markets, investment incentives

1. Introduction[*]

Historically energy storage has been viewed as an alternative for a utility to building peaking generation, since it could be used to serve on-peak load with off-peak generation. Given this somewhat limited view of energy storage's role within power systems, storage investment in the United States languished in the 1980s and 1990s when the cost of peaking generation was relatively low. It is only more recently, with numerous developments in the electricity industry, that energy storage has experienced a renaissance. These developments that have increased interest in energy storage include: increases in the cost of generation, transmission, and distribution; the development of markets for various electricity services; discovery of novel roles that energy storage can play within energy systems; and the push for more renewable energy. This increased interest in energy storage has spurred a great deal of storage-related research and development, including technology improvements and studies of the value propositions that storage presents.

The analysis of energy storage value has shown that storage can play many more roles than simply shifting generation loads, and that it could potentially provide value for entities other than a utility. Despite all of this storage-related research, however, many unanswered questions remain. For instance, most storage analyses have considered a single use of storage by a single entity, without considering complementary or competing uses of storage or how inefficiencies could be created if storage is overly balkanized. Along the same lines, many analyses of storage have focused on the private value of storage to a particular entity, without necessarily considering the external impact of storage to others. Similarly, there are myriad regulatory and policy decisions that can affect how storage is used, what values different parties derive from storage, and whether storage investment is economic. This paper provides a survey of the history and future of storage development in the US and outstanding policy and analytical questions relating to storage.

The remainder of the paper is organized as follows. Section 2 discusses the history of storage development in the US, and some of the limitations in how storage investment was justified beginning in the 1970s, when much of the US's current storage capacity was built. Section 3 discusses potential uses of storage beyond serving as an alternative to peaking capacity and uses of storage by entities other than a traditional vertically-integrated utility. Section 4 lays out some outstanding policy and research questions related to energy storage and discusses how questions such as regulation, market products, and ownership can greatly affect the true value of storage and incentives for and efficiency of storage use and investment. Section 5 concludes.

2. History of Energy Storage in the US

Up until recently, energy storage has been viewed primarily as an alternative to a utility having to build peaking generation. Due to the diurnal load pattern, utilities typically build a mix of baseload, intermediate, and peaking generators. Because peaking generators generally have low capacity factors[1], generators with low capital and high generation costs, such as oil- and natural gas-fired simple-cycle combustion turbines (CTs), are built to serve peak loads. Energy storage offers an alternative to building a peaking generator, since storage can be charged when loads are low and

[*] The author would like to thank Paul Denholm and Thomas Jenkin for past collaborations and discussions related to energy storage that have helped inform this paper. Armin Sorooshian provided helpful conversations, suggestions, and ideas as well. The opinions expressed in this paper (along with any errors) are those of the author alone, and do not necessarily reflect the beliefs of anyone else. Email address: sioshansi.1@osu.edu (Ramteen Sioshansi)

[1] In some extreme cases, a peaking generator may only operate a handful of hours per year when the system load is at its extreme peak.

discharged during the peak. This allows the utility to serve the peak load without the need for added generating capacity. Moreover, because the marginal cost of energy during off-peak hours is generally much lower than that of the typical peaking generator, this presents a substantial fuel cost savings for the utility.

Although a few pumped hydroelectric storage (PHS) plants had been built in US by that time, interest in storage began in earnest in the early 1970s. This interest was spurred primarily by massive increases in the cost and disruptions in the supply of oil and natural gas, especially the oil crisis of 1973 and natural gas shortages in the mid-1970s. These events also raised concerns over fuel supply, leading to the Powerplant and Industrial Fuel Use Act of 1978 (FUA). The FUA significantly limited the extent to which powerplants powered primarily by oil and natural gas could be built and instead encouraged the use of coal, nuclear, and other alternative fuels for electricity generation. As a result, many utilities saw energy storage as an attractive option to serve peak loads—the combined effects of fuel prices and the FUA made traditional peaking technologies prohibitively expensive and legally difficult to build, and utilities expected to have access to low-cost baseload generation to charge energy storage with. Denholm et al. (2010) show the effect of oil and natural gas price increases on the relative costs of serving on-peak loads with several different types of peaking generators or with energy storage. They show that energy storage enjoyed a considerable price advantage over most of the 1970s and 1980s, with a cost savings of close to \$90/MWh in some cases. Even with decreases in oil and natural gas costs and the introduction of more-efficient combined-cycle gas turbines (CCGT), beginning in the mid-1980s, energy storage still had a fuel cost savings over conventional generation.

In order to rationalize investment in energy storage, the energy cost savings would have to outweigh any capital cost premium of energy storage above that of a comparable generator. During the 1970s and 1980s, a peaking generator was not considerably less expensive to build than a PHS, and as such energy storage was economic on the basis of on-peak load cost alone. As a result, the mid- to late-1970s saw much of the US's 20 GW of PHS capacity built or initiated and significant research and development in other storage technologies undertaken (*cf.* ASCE (1993)). By the 1980s, however, most investment and interest in energy storage ended due to the decline in natural gas and oil prices, improvements in the efficiency and flexibility of CCGT generators, and the repeal of the FUA in 1987. Even with more recent increases in natural gas prices in the 2000s and decreases in coal costs, energy storage was still not seen to be an economic investment due to CCGT generators having relatively lower capital costs than energy storage. For instance, in the 1970s PHS and CCGT generators were estimated to have comparable capital costs, whereas by the 2000s PHS was estimated to cost twice as much to build as a CCGT generator. Moreover, public concerns over nuclear generation limited the nuclear build-out in the US, eliminating an expected source of low-cost off-peak energy that helped justify storage development in the 1970s. In addition to the loss of its cost advantage, energy storage development was also stunted during this period due to the fact that storage investment decisions were made almost exclusively on the basis of energy-related cost savings, largely ignoring other benefits and values provided by storage. For instance, EPRI (1976) suggests comparing energy storage to conventional generation on the basis of the value of energy and firm capacity alone, without any quantification of other benefits. As will be discussed in section 3, energy storage can provide many benefits to a utility, its customers, and others beyond reducing the cost of serving the utility's on-peak load. Even if these additional value streams are relatively smaller than the generation-cost savings, excluding them from the comparison of storage and generation can bias the results against storage investment since many of these benefits are unique to energy storage. As we discuss in sections 3 and 4, one of the difficulties inherent in including these additional value streams in an economic analysis of storage investment is that they can be quite difficult to quantify. Moreover, if energy storage will be used for multiple purposes, these uses may interact with each other, yielding non-additive benefits. We provide some examples in section 4 that highlight the fact that depending upon the particulars of a power system, these uses of storage may be complementary or competing with one another. This implies that there will not typically be a single 'rule of thumb' that can be used to quantify these benefits and a detailed analysis would likely be required in each individual case to determine what the full value of energy storage would be. The computation of these values is further complicated by the fact that some of the benefits of storage may not accrue to the potential investor. This will, in some cases, be dependent upon the regulatory structure and treatment of a storage investment.

Even more recently, with these additional benefits of storage having been identified, storage investment has been largely non-existent. Denholm et al. (2010) attribute this to the fact that utilities view these other values of energy storage as being uncertain and as such have preferred investing in traditional generation, which they perceive as being less-risky investments. Besides completion of previously-initiated PHS plants, most storage plants that have been built recently have been demonstration plants. This includes a 110 MW compressed-air energy storage plant built in McIntosh, Alabama in 1991, and a handful of flywheel, superconducting magnetic energy storage, and sodium-sulfur (NaS) battery installations.

3. Potential Uses and Benefits of Storage

Beginning in the 1970s, a great deal of research has been undertaken to identify other potential uses of energy storage beyond serving a utility's on-peak load. These uses have generally been classified into five broad categories: generation-related applications, ancillary service applications, transmission and distribution (T&D) applications, customer applications, and renewable integration. We will provide a brief, but by no means completely comprehensive, discussion of each of these application areas. Interested readers should consult papers by EPRI (2003); Eyer et al. (2004, 2005); Denholm et al. (2010); Eyer and Corey (2010) for a more comprehensive discussion of these potential uses and especially some of the technical characteristics and requirements associated with each.

3.1. Generation-Related Applications

Generation-related applications are overall quite similar to the traditional role of energy storage as an alternative to building or using high-marginal cost generation to serve load. In contemporary discussions, generation-related applications are typically divided into two uses: using existing energy storage to shift generating loads from a more- to less-expensive generator, or building energy storage as an alternative to building a conventional generator. It should be apparent that this application of energy storage is quite similar to the traditional view of energy storage as an alternative to building peaking generation, and as such we only expand upon the discussion in section 2 by highlighting how these applications of energy storage are facilitated by restructured electricity markets.

3.1.1. Generation Shifting

The concept of using energy storage to shift generation loads from more- to less-expensive generation is perhaps the best-known and most-studied application of energy storage. In a restructured electricity market, this use of storage is facilitated by energy storage being used to arbitrage intertemporal energy price differences based on the market-clearing price (MCP) or locational marginal price (LMP). Since these MCPs and LMPs indicate the marginal cost of serving an incremental unit of load at each point in time, if inexpensive energy is purchased to charge a storage device that is then discharged to sell more-expensive energy, this energy arbitrage will shift generation from a more- to less-expensive generator[2].

[2] It has been suggested by some authors that the term 'arbitrage' is a misnomer for this use of energy storage, since arbitrage requires the simultaneous trade of similar products in multiple markets with different prices. Depending on how exactly energy storage is scheduled in an energy market and how one defines 'similar products,' this use of energy storage can be thought of as arbitrage since the purchases and sales of energy during different time periods can be scheduled simultaneously in a centrally dispatched market. For instance, if storage is bid into multiple hours of a day-ahead energy market, it can simultaneously be dispatched to purchase and sell energy in multiple hours. Whether this

This use of energy storage has been studied by a number of authors, including Graves et al. (1999); Figueiredo et al. (2006); Walawalkar et al. (2007); Sioshansi et al. (2009). These authors all examine this use of energy storage using historical price data under a 'price-taking' assumption, in which the energy storage is assumed to be sufficiently small compared to the overall market that storage use has no impact on energy prices. These analyses demonstrate that depending upon the market under consideration, this energy arbitrage could provide the storage owner a gross revenue (not including any capital costs associated with storage development) of between $29 and 240/kW-year. These value differences are in large part a reflection of differences in the generation mix and fuel costs in different power systems. For instance, Sioshansi et al. (2009) note that in the PJM Interconnection coal-fired generators are often marginal overnight whereas gas- or oil-fired generators are marginal during the day. As such, energy storage can arbitrage significant differences in the price of these generating fuels. In a system such as the California ISO, on the other hand, natural gas is almost always the marginal generating fuel, and diurnal price differences stem primarily from differences in the heat rates of CCGTs and CTs—yielding comparably lower differences in on- and off-peak energy prices and commensurately lower arbitrage values.

These analyses have also shown that while multiple hours of charging and discharging capacity are needed, much of the potential arbitrage value can be captured with roughly eight hours of storage. While greater storage capacities will yield some increases in arbitrage value, the marginal value of these incremental hours of storage rapidly diminish. Thus the incremental cost of increasing the hours of storage will be a relatively important factor in determining whether this use of storage will be economic, when investment costs are taken into account. Sioshansi et al. (2009) also show that the efficiency of the storage technology will greatly influence the economics of energy arbitrage and that the efficiency will have a multiplier effect. For instance, they show that increasing the roundtrip efficiency of energy storage from 70 to 80% will increase arbitrage revenues by more than 30%. The reason for this result is that less-efficient storage must charge more hours for a given number of hours of discharge, and that these added hours will have higher energy prices.

Sioshansi et al. (2009) relax the price-taking assumption and consider the impact of large-scale storage that could affect the price of energy. In such a case, the value of arbitrage will generally be reduced because charging storage will tend to increase the off-peak price of energy (as more-expensive generation is needed to serve the charging load) whereas discharging storage will tend to decrease the on-peak price of energy (as expensive generation is displaced by the storage). This analysis shows that the arbitrage value of energy storage in PJM could be diminished by up to 20% compared to the price-taking case, depending on the particular year and the storage size considered. They show, however, that although this price responsiveness will reduce the arbitrage value of energy storage, there are net external welfare benefits since consumers have lower energy costs.[3]

The analysis of the price-responsive case is based, however, on an assumed linear relationship between energy prices and generating loads. Thus this analysis does not account for potentially more disruptive price effects that energy storage could have. It should also be noted that the power (as opposed to energy) capacity is the storage size that has the greatest impact on the value of storage absent the price-taking assumption. This is because the amount of energy that can be charged or discharged in each hour, which will depend on the power capacity of storage, will determine the extent to which the on-and off-peak energy price is influenced by the use of storage. PHS units that are part of restructured markets are currently used for generation shifting. These units are typically either scheduled bilaterally with other generators and load-serving entities (LSEs), or if the PHS owner is also a generator and LSE the operation of the PHS is co-optimized with the firm's other activities, or

(Contd.)

technically qualifies as arbitrage depends on whether one considers energy delivered in different hours to be similar products or not.

3 There are, in fact, wider welfare effects, because generators will have lower profits. Consumer welfare gains are, however, shown to outweigh these profits losses yielding a net social welfare gain.

bid into a centrally-committed market that co-optimizes the use of the storage with other generating units. The California ISO, for instance, has special market rules and provisions for bidding and dispatching energy-constrained generators, which includes energy storage.

3.1.2. Capacity Deferral

Capacity deferral refers to building or using energy storage as an alternative to generating capacity in a power system. As described in section 2, a vertically-integrated utility would traditionally compare the expected capital and energy cost of energy storage to that of a generator and build whichever provided capacity at a lower cost. In a restructured electricity market, on the other hand, generation investment decisions are meant to be made in a decentralized fashion by firms that respond to market prices. If a firm finds that expected energy revenues are greater than expected investment and fuel costs, then the firm should build generating capacity. Because incumbent generators are supposed to incorporate scarcity prices in their generation bids, energy prices should include scarcity rents and signal when capacity investment is needed. In a restructured market, energy storage should be built in much the same way. If the expected pattern of energy prices suggests that the revenues from energy transactions (i.e. net energy arbitrage revenues) outweighs the investment cost, then a firm would find it economic to invest in energy storage and do so. In some markets energy prices alone do not properly signal investment, since prices are artificially suppressed.

This price suppression is typically caused by administrative rules, such as price- or offer-caps, which are intended to prevent generators from exercising market power. In other cases, generators may curtail their bids for fear of regulatory or legal action from competition or regulatory authorities. This price suppression can result in insufficient amounts of capacity investment (on the basis of energy prices alone) since the artificially low energy prices are not able to sustain necessary capacity investments. For this reason energy markets often include separate capacity markets, which provide incumbent or new generators capacity payments that are intended to make up the 'missing money' created by the price suppression (Finon and Pignon (2008), for instance, provide a survey of design proposals and empirical analyses of these types of capacity markets). These capacity payments are typically linked to the availability of each generator, and could be a function of its capacity factor during peak-load periods. In such a restructured market with energy and capacity payments, investments in energy storage would be made in a similar manner to an energy-only market—expected arbitrage and capacity payment revenues would be compared to expected costs, and storage would be built if it appears economic on this basis.

One issue in estimating the value of such a capacity payment, and how it would affect storage economics, is that it is not clear how the capacity value of energy storage should be determined. Because energy storage is effectively an energy-limited generator, with the energy limit determined by the operation of the storage, how storage is used will affect its capacity value. For instance, if energy storage is used primarily for energy arbitrage one would expect that it would typically be discharged during high-load hours when energy prices are high. If these high-load hours are also hours with high loss of load probabilities, the effective capacity of the storage would be relatively low since it would tend to not have energy available during hours in which capacity is most needed. On the other hand, if a storage operator knows that its capacity payments would vary as a function of its storage operation decisions, it may co-optimize these decisions to maximize the sum of arbitrage and capacity payments. Given these difficulties, most authors who have examined storage economics have not directly addressed this issue. For instance, Sioshansi et al. (2009); Sioshansi and Denholm (2010a) note that energy storage would likely be eligible for some capacity payment, but only offer the capacity value of a CT as a likely upper-bound on the payment that energy storage would receive.

Tuohy and O'Malley (2009) estimate the capacity value of PHS in a power system with high penetrations of wind. Their estimation technique assumes that storage operations are co-optimized with conventional generators to minimize system dispatch costs. This cost minimization is effectively equivalent to a storage owner maximizing the arbitrage value of storage. Once the operation of storage is determined, they use the amount of energy during the 100 highest-load hours to estimate the effective capacity of the PHS. Their estimation technique does not, however, take into account the fact that a storage owner may keep more energy in storage to increase the capacity value and payment of the device. For instance, they show that in some cases a 500 MW PHS plant provides an effective capacity of less than 400 MW, which is potentially less than what it would provide if the storage operator is concerned with maximizing the sum of arbitrage and capacity revenues.

Finally, it is worth noting that many of the other applications that will be discussed below could potentially factor into the decision of a firm to invest in energy storage. For instance, if energy storage could be used for arbitrage purposes and to sell ancillary services (which will be discussed in section 3.2), then presumably a firm would make its investment decision on the basis of total revenues from energy arbitrage, ancillary services, and capacity payments, as applicable.

3.2. Ancillary Service Applications

The term ‘ancillary services’ refers to a range of reserve capacity services that are needed to properly operate a power system. Because power systems require that demand and supply of active and reactive power be perfectly balanced at all times, and due to uncertainty in real-time demand and supply, power system operators generally keep reserves available to handle unforeseen demand or supply variations. Moreover, because these supply and demand deviations can occur on different time and duration scales, market operators typically keep different types of reserves available. The advent of restructured energy markets, which typically include organized markets for these services and provide transparent price information, make these ancillary services a potentially important and lucrative application for energy storage. In such markets, generators and energy storage owners offer their capacity into the market. If the capacity is reserved by the market operator, the ancillary service provider is obligated to have sufficient capacity available to respond to any real-time requests for energy from the market operator within the timeframe specified by the type of ancillary service. Typically, the ancillary service provider is paid for making its capacity available, independent of whether the energy is called in real-time, and supplemental payments are made if energy is called in real-time.

Energy storage is potentially very well-suited to providing ancillary services, since most of the value of ancillary services is associated with the capacity as opposed to energy of the storage device. Moreover, many energy storage technologies have much faster response times than conventional generators and are able to adjust their real-time output nearly instantaneously. Finally, many ancillary services require generators to be online and synchronized with the system, which effectively requires that these generators be operated at part-load. This places an added fuel cost on a conventional generator offering ancillary services, since these generators are often much less efficient when operated at part-load, or because in some cases a generator is kept online solely for the purpose of providing ancillary services. Many energy storage technologies do not incur such a cost, since their capacity is nearly instantaneously available without incurring any fuel or operating cost.

Ancillary services are typically divided into several different service types, which are characterized by varying response times and service qualities. The highest-quality ancillary service, frequency regulation, is used to correct moment-to-moment changes in power supply and demand. As such regulation service requires very fast response times (oftentimes less than a minute). Some markets treat regulation service as a single product. A regulation service provider in such a market that offers x MW of regulation capacity can be called upon to either increase or decrease its generation level in real-time by up to x MW. Other markets divide regulation into two separate services—regulation up and regulation down—where a regulation up provider can only be called upon to increase its generation level, whereas a regulation down provider can only be used to decrease its generation level (an entity that offers both regulation up and down can be called upon to increase or decrease its generation level). Kempton and Tomi´c (2005); Walawalkar et al. (2007); Denholm and Letendre (2007); Tomi´c and Kempton (2007) estimate the value of regulation services using historical price data from a number of markets in the US and under a price-taking assumption, and show that the value of these services can range between $163 and 429/kW-year. One major issue with these estimates of regulation-related value is that regulation markets are typically quite 'thin,' with a relatively small amount (compared to the aggregate generating capacity of the market) transacted. Thus, tens or hundreds of MW of storage capacity entering the regulation market could severely suppress the price of regulation services.

The viability of the regulation application is clearly dependent upon a storage technology having fast response times and low power capacity costs. Moreover, Walawalkar et al. (2009) note that the roundtrip efficiency of the storage technology may also be a critically important determinant, depending upon the treatment of the regulation product in the market. This is because energy storage with a low roundtrip efficiency that receives many successive regulation up and down calls may be depleted due to the efficiency losses associated with energy going through the storage cycle. If the market treats regulation up and down as a single service, a storage owner may have to curtail the amount of regulation that it offers in the market to prevent such a depletion. If, on the other hand, regulation up and down are treated as two separate products, the storage operator could offer more regulation down than up in an effort to prevent the storage from being depleted, thereby also increasing the value of the regulation application. Another type of ancillary service is contingency or reserve capacity, which includes spinning and non-spinning reserves. These reserves are typically used for large and prolonged supply imbalances, for instance due to a forced generator or transmission outage. As such, these types of reserves typically have slower response times but can require that a provider be able to sustain its output for several hours in the event of a real-time contingency. Thus these applications may require multiple hours of storage capacity in order to meet specifications of the reserve products—although these specifications do vary to some extent between different markets.

Denholm and Letendre (2007) estimate the value of these types of reserves to be in the range of $66 to 149/kW-year. An added advantage of contingency reserves is that the quantity procured in the market is significantly greater than the amount of regulation services (contingency reserve requirements are often determined by the size of the largest contingency in each hour, for instance the generating capacity of the largest committed generator), thus the price of these services would be less prone to suppression from energy storage entering the market. This price suppression could nevertheless become an issue with higher penetrations of energy storage. For example, Sioshansi and Denholm (2010b) examine the benefits of using plug-in hybrid electric vehicle (PHEV) batteries as a source of contingency reserves in Texas and show that once the PHEV fleet size exceeds 15% of light duty vehicles the contingency reserve market is effectively saturated.

Other ancillary service products include black-start and power quality-related services. Black-start provides energy to the power system to recover from a system failure by helping other units restart and providing a reference frequency for synchronization. Although some markets price black-start capacity, the value of energy storage providing black-start services has not been thoroughly analyzed. Power quality services include active and reactive power adjustments that are used to prevent or minimize local voltage deviations, outages, or harmonics. The value or benefit of power quality-related applications are difficult to estimate because virtually no markets exist for these services. These markets do not exist because most power quality-related services can only be provided by a small set of generators within a local area (in some extreme cases, there may only be a single generator that can provide services in an area). As such, a market for these services would be prone to exercise of market power. Instead, the provision of these services is often mandated by the system operator or by reliability standards and the cost of providing the service is socialized to customers through rate-basing or other similar mechanisms. A potential external benefit of using energy storage for power quality-related purposes is that entry of energy storage could make the market for these services more competitive. In such a case, the cost of these services could be better-determined through an organized market and allocated to customers more efficiently.

3.3. Transmission and Distribution Applications

In addition to generation- and reserve-related uses, energy storage can also serve as an alternative to building, upgrading, or expanding T&D infrastructure. This application of energy storage requires storage be built in specific locations within the T&D network where capacity or other technical limits threaten the ability of loads to be served reliably or economically. For example, consider a radial transmission line that is prone to congestion but is not continuously congested. Traditionally, the congestion would be relieved by either expanding capacity of the transmission line or siting a generator on the constrained side of the transmission line. If the transmission line is upgraded, this would relieve the transmission constraint, whereas a generator sited at the transmission-constrained bus could be used as an alternative to importing energy, which would reduce flows on the transmission line and relieve the constraint. Properly-sized energy storage[4] that is sited on the constrained side of the transmission line could also be used to relieve the constraint in a similar fashion to the generator. This would be done by charging the storage when the transmission line is unconstrained and discharging it when it would otherwise be constrained. The discharged energy from storage would then be used as an alternative to importing energy along the transmission line. As the example above suggests, transmission-related applications of energy storage are highly site- and case-specific. The value of this application will depend on typical power flows within a T&D system and identification of potential sites that are prone to congestion and suitable for energy storage installations. While viability of this application will depend on the technical characteristics of the storage technology meeting the congestion patterns that are being relieved, certain technologies may not be viable due to geographic or siting issues at certain locations. For instance, PHS may not be a viable technology to relieve most transmission bottlenecks in urban areas, since the requisite geology is typically not present at these locations.

Similarly, residents in urban areas may object to some storage technologies being installed (which is oftentimes an impediment to siting generation or transmission as well). Although the value and benefits of this application are highly site-specific, they have been estimated by examining differences in the arbitrage value of energy storage at different buses within a power system. These differences in arbitrage value stem from differences in LMPs at buses within the transmission network. Because these LMPs include the marginal cost of transmission congestion, differences in the arbitrage value of energy storage at these sites reflect the value of energy storage relieving transmission constraints. Walawalkar et al. (2007), who examine the arbitrage value of energy storage in the New York ISO market, also examine differences between the value of arbitrage in New York City and the rest of the state. Their estimates show that while arbitrage values outside of New York City range between \$29 and 84/kW-year, this value increases to \$87 to 240/kW-year in New York City. Similarly, Sioshansi et al. (2009) examine differences in arbitrage value at different buses in the PJM Interconnection market, and show a close to \$40/kW-year 'swing' in arbitrage value between the most- and least-congested locations within the network. It should be noted that in addition to helping estimate the value of transmission-related applications of energy storage, these analyses also show that LMPs signal where in a transmission network energy storage could be used for transmission-related applications. Another advantage to building energy storage, as opposed to transmission, to relieve a transmission constraint is that transmission capacity investments are often 'lumpy' and cannot necessarily be scaled to meet the exact needs of relieving a particular congested line (Sauma and Oren (2006) discuss this issue with transmission investments).

[4] Eyer et al. (2005) discuss how power and energy capacity requirements for this application can be estimated.

Greenblatt et al. (2007) note, however, that energy storage can typically be scaled to an exacting size, meaning that the amount of incremental capacity could more closely match what is needed to relieve the constraint, potentially reducing the extent to which the system would be ‘overbuilt.’ Just as energy storage can be used to relieve transmission constraints, it can also be used for distribution-related purposes. If a distribution system does not have sufficient capacity to serve customer loads, the LSE would traditionally relieve this bottleneck by upgrading the distribution system. If, however, the distribution system in question is not constantly capacity-constrained, energy storage can installed on the constrained side of the distribution system to relieve the constraint. The energy storage can then be charged when the distribution system is unconstrained and discharged when the distribution system would otherwise be constrained. Because the basic principle of distribution-related applications is the exact same as transmission-related uses, the same general issue of the value of this application being extremely site-and case-specific will also arise. Moreover, because energy is not priced at the distribution level, LMPs will generally not provide price signals for investment in energy storage for these purposes. This lack of transparent price data also makes it difficult to estimate the value of these types of services. Despite these difficulties, some pilot storage facilities have been developed for distribution-related purposes. For instance, Nourai (2007) discusses a 1 MW NaS battery facility that American Electric Power (AEP) installed in a community in West Virginia to relieve a distribution constraint.

In addition to helping relieve T&D system constraints, this use of storage can have some ancillary benefits. Nourai et al. (2008) note that because T&D losses are a function of line loading, using energy storage to level T&D loads can reduce these losses. Using AEP’s NaS battery in West Virginia as an example, they estimate that the load-shifting done to relieve the distribution constraint also reduces annual T&D losses by about 181 to 336 MWh/year. Another benefit of building energy storage as opposed to T&D upgrades is that energy storage can help increase T&D asset utilization.

Traditionally, the T&D infrastructure in a power system must be built to serve the peak demand. If this peak demand is only observed a few hours of the year, the marginal unit of T&D capacity will be used relatively infrequently. Because energy storage levels loads and demands its use will increase T&D (as well as generation) asset usage and reduce the need to build infrastructure that would only be used rarely during extreme peaks. Another benefit of energy storage at the distribution level is that it can be used to provide emergency energy services during a system outage. For instance, if a line outage further up the T&D network or a generator failure would disrupt service to a community, energy storage that is located at the distribution level can be used to provide emergency energy services to customers for a limited time.

3.4. Customer Applications

The applications described thus far are uses of energy storage by generators, utilities, LSEs, and power system operators to reduce investment costs or increase system reliability or efficiency. In many cases customers can use storage in similar ways to either reduce the cost or increase the reliability of their service. These uses are generally classified into two application areas: managing service costs, and improving service reliability and quality. As the discussion below suggests, these applications are extremely specific to the customer and the LSE providing energy services, and as such the value of these applications cannot be estimated in general.

3.4.1. Managing Energy Costs

A customer facing a tariff that either distinguishes between the time of energy use or includes rates based on the customer’s load factor, can use energy storage to reduce electricity service costs. In the first case, in which a customer pays a time-variant price for energy, such as a time of use or real-time pricing (RTP) tariff, energy storage can be used to shift demand from periods with high prices to lower-price periods. For example, suppose a customer faces a lower retail electricity price overnight than during the day. By charging energy storage overnight and discharging it during the day, this customer could reduce the net retail cost of its energy.[5] This use of energy storage is clearly akin to the energy arbitrage and generation shifting application described in section 3.1.1. The only difference is that whereas energy arbitrage decisions are made on the basis of wholesale electricity prices, such as the MCP or LMP, customers would make arbitrage decisions based on the retail rates that they face. Indeed, if customers face a RTP tariff whereby the retail prices are set by the MCP or LMP, then this use of energy storage by a customer would yield the same result as the generation shifting application.

Energy storage could also be used by customers facing a demand factor-based tariff to reduce costs. Some customers, particularly large industrial and commercial loads, are often charged a rate that is a function of its total energy use as well as the demand factor of its load pattern[6]. This demand factor charge is included in the tariff to allocate the cost of building the power system to meet the system peak to customers that contribute to the peak. In some cases this is achieved by including a charge that depends solely on the customer's peak power demand. Regardless of how the specific pricing mechanism is employed, energy storage could be used by a customer that has a time-variant load pattern to level its load pattern and improve its demand factor. For instance, if a customer typically has a four-hour peak in its electricity demand every day, a four-hour storage device could be used to shift some of this load to a shoulder period with a lower load. Note that if the customer is also charged a time-variant energy price, and the customer's demand is correlated with the retail price, this use of energy storage could have the ancillary benefit of reducing retail energy charges.

3.4.2. Improving Service Quality and Reliability

As with the power quality-related application discussed in section 3.2, a customer could also use energy storage to improve the quality of power[7] used in its electric devices, by using energy storage to buffer any real-time active or reactive power imbalances between its load and grid energy supply. The value and practicality of this use would depend upon the quality of power provided by the LSE and whether the customer has devices or equipment that are highly sensitive to voltage or frequency deviations or other power quality-related issues. Similarly, a customer that is concerned about or experiences service disruptions, could use energy storage to provide energy during a service disruption. This is a relatively well-known and used energy storage application, since many customers have uninterruptible power supplies (UPSs) installed on computers and other equipment. It has been suggested that the UPS concept could be expanded by building storage devices that could support an entire building during a service outage.

3.5. Renewable Integration

Much of the recent interest in energy storage has been spurred by the push for greater use of renewable energy. Because many renewables, including wind, solar, wave, and tidal energy, are not fully dispatchable and their real-time availability can be highly variable and uncertain, integrating these resources into power systems presents unique challenges. It has been suggested that energy storage can be used to manage these integration issues. A number of authors, including Sørensen (1981); Cavallo (1995); Denholm et al. (2005); Paatero and Lund (2005); DeCarolis and Keith (2006); Succar et al. (2006); Greenblatt et al. (2007); Swider (2007); Black and Strbac (2007); Abbey and Joos (2007); Garcıa-Gonzalez et al. (2008); Arsie et al. (2009) have examined the use of energy storage to reduce the impacts of the variable and unpredictable nature of wind availability and the broader

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[5] This use implicitly requires that the difference in the retail rates between the two periods outweighs the roundtrip efficiency losses of the storage device.

[6] The demand factor is defined as the ratio between the average and peak power demand of a customer.

[7] The term power quality refers to the same quality metrics discussed in section 3.2.

economics of energy storage and wind. While these analyses have focused on wind integration, many of the same issues will arise with other renewables, and energy storage could play very similar roles in mitigating these impacts.

The renewable-related applications of energy storage are typically classified into five broad areas that we will discuss: increasing renewable value, firming renewable capacity, reducing minimum load violations, improving renewable power quality, and reducing transmission needs for renewables.

3.5.1. Increasing Renewable Value

The economic viability of many renewables, especially wind, suffers from the fact that real-time renewable availability can be negatively correlated with energy prices in many power systems. This issue is further exacerbated with higher renewable penetrations, because the ability of conventional generators to exercise market power is suppressed if demand for their generation is reduced. Thus, conventional generators will tend to exercise less market power, resulting in lower energy prices, during periods in which real-time renewable availability is high. Green and Vasilakos (2009); Twomey and Neuhoff (2009) both examine this issue as it relates to wind generation in the UK market using supply function equilibrium (SFE) and Cournot models to represent the strategic behavior of the conventional generators. They show that depending upon the amount of wind in the system, the average price of energy could be suppressed by more than £65/MWh and the value of wind generation could be more than £20/MWh lower than the value of conventional generation. Sioshansi (2010a) does a similar analysis in the Texas market using an SFE model, showing the same results that higher penetrations of wind will suppress the price of energy, but that this price suppression will be concentrated in periods with high wind availability, reducing the value of wind more than conventional generation.

Sioshansi (2010a) further shows that by coupling wind generation with energy storage, the value of wind can be increased by storing wind energy during periods in which the energy price is relatively low or would be overly suppressed by selling wind energy, and discharging storage during periods with higher prices. His results show that depending on the competitiveness of the market and the amount of storage, the average price of wind from a 10 GW wind generator can be raised by between \$0.22 and 13.18/MWh translating into an increase in the annual profit of the wind generator of between \$4 million and \$310 million. One negative consequence of this use of energy storage that he shows, however, is that consumer energy costs will increase and conventional generator profits will decrease and that these welfare losses will outweigh the increase in the wind generator’s profits, meaning that there will be a net social welfare loss.

It should be noted that this application of energy storage is not limited to wind generation and does not require a high renewable-penetration case, in which renewable generation suppresses energy prices. For instance, Sioshansi and Denholm (2010a) examine the use of thermal energy storage (TES) with concentrating solar power (CSP) plants in the southwestern US under a price-taking assumption, in which energy prices are fixed and do not respond to CSP output. They show that TES can significantly increase the value of the CSP plant’s output through the same generation shifting, and that in some cases this increase in value can justify the incremental cost of adding TES to a CSP plant. This result highlights the fact that energy storage can play an important role in increasing the value of renewable generation, even in a case with low renewable penetrations wherein renewable generation would have a negligible effect on the energy price. This is because whereas the output of the renewable generator is non-dispatchable, the joint output of the renewable generator and energy storage device is at least partially dispatchable[8].

[8] It will not be fully dispatchable, depending upon the relative size of the storage and renewable plant, when the storage plant is capacity-constrained due to previous storage dispatch decisions.

This dispatchability can increase the value of the renewable generator by allowing the renewable owner to dispatch the output of its joint renewable and storage plant during periods with the highest energy price. This result also shows that energy storage can be valuable for renewables other than wind. In many power systems electricity loads are driven by building cooling, which will tend to be highly correlated with real-time solar availability. Because of the positive relationship between generating loads and energy prices, solar availability will tend to be positively correlated with energy prices in power systems with cooling loads. Nevertheless, Sioshansi and Denholm (2010a) show that since cooling loads can lag solar availability by a few hours, energy storage can increase the value of solar output.

3.5.2. Capacity Firming

Energy storage can also be coupled with one or more renewable generators to firm or level the output of the joint storage and renewable plant. This capacity firming can be done by a system operator wishing to increase the reliability of a system with high renewable penetrations, as well as by a renewable generator that wishes to level the output of its renewable generator. In the case of system reliability, many system operators currently handle renewable variability by increasing ancillary service procurements from conventional generators and using that capacity to balance any supply deviations[9]. A number of authors, including Sørensen (1981); Cavallo (1995); Paatero and Lund (2005); Black and Strbac (2007); Garcıa-Gonzalez et al. (2008), have examined the use of energy storage as an alternative to conventional generation for balancing renewable variability, using the specific case of wind integration, showing that energy storage could provide the needed system flexibility. Despite these findings, Milligan et al. (2009) note that empirical evidence suggests that energy storage is not needed for handling wind variability until wind penetrations rise to at least 20% of the system's capacity. This result is due, in part, to the fact that wind capacity is most power systems is built in geographically diverse areas, and the lack of correlation between wind availability between these regions will tend to reduce the variability of net real-time wind availability to the system as a whole. While these analyses have focused on accommodating wind variability, the results should apply to renewables in general. Other renewables, such as solar, will raise similar integration issues due to resource variability and energy storage could play a similar role in accommodating this variability.

Energy storage could also be used by an individual renewable generator that wishes to reduce variability in the output of its renewable plant. This application would only arise if a renewable generator faces some penalty from supply variability, for instance through imbalance charges levied by the system operator or through similar penalties in a bilateral contract to sell its energy. In such a case, a renewable generator could use energy storage to level the output of its combined renewable and energy storage plant. This application typically does not appear in practice because most system operators' market rules include specific provisions to accommodate the variable nature of renewable generators. For instance, Sioshansi and Hurlbut (2010) describe the market rules in Texas, which virtually eliminate imbalance charges for renewable generators that allow the system operator to conduct day-ahead resource forecasting and scheduling. As such, these rules eliminate the need for an individual renewable generator to use energy storage to level its output and firm its capacity. The rationale behind these types of rules is that because geographically diverse renewable resources will tend to have low correlation in their real-time availability, each individual renewable generator using energy storage in this way would be suboptimal. To see this, consider two renewable generators and suppose that the output of one is above and the other is below its scheduled generation level. If each has an energy storage device, they will simultaneously charge and discharge energy storage to level their outputs and minimize imbalance charges. This is, however, an inefficient solution since the

9 Lee and Yamayee (1981); S¨oder (1993); Doherty and O'Malley (2005); CAISO (2007), for instance, discuss how ancillary service requirements should be adjusted with variable generators, such as renewables.

aggregate output of the two generators will be close to their aggregate scheduled generation—and no energy losses would be incurred from energy going through the two storage devices.

3.5.3. Reducing Minimum Load Violations

Many conventional generators have minimum load levels, above which their generation level must be when they are online. These minimum-load constraints are especially pressing for baseload generators, such as coal and nuclear generators, and CCGT plants. As renewable penetration levels increase, these minimum load constraints can limit the amount of renewable energy that the market can accept, since some conventional generation capacity will likely have to be kept online (above its minimum load level) in order to ensure system reliability or for other reasons. As such, renewable generation would have to be curtailed or 'spilled' during periods with either low loads or high renewable availability. Denholm and Margolis (2007) cite the example of the Danish power system, which has high wind penetrations and relies on combined heat and power from thermal generators. During cold winter nights on which electric loads are low and heating needs and wind availability are high, the output of wind generators have to be curtailed. Denholm and Margolis (2007) go on to examine the impact of minimum-load constraints on the ability of a power system to accommodate solar photovoltaic (PV) generation, showing that inflexible systems may have very high marginal PV curtailment rates. Energy storage could clearly play a role in reducing such renewable curtailment, by charging storage when minimum-load constraints prevent the system from accepting all of the renewable energy available in real-time.

3.5.4. Improving Power Quality

Many renewables, especially wind generators, can introduce power quality issues. In the context of wind, these can be frequency or voltage deviations, harmonics, or other dynamic or transient stability issues that typically arise due to wind gusts or changing electrical conditions in the power grid. These power quality issues can arise with other renewables as well. As with the power quality applications discussed in section 3.2, energy storage could be used to reduce these impacts of renewables on power quality and grid stability. Alternatively, recent advances in wind turbine design have reduced the extent of these issues, and similar advances in the design of solar and other renewable generators could reduce the need for energy storage for power quality-related uses.

3.5.5. Reducing Transmission Congestion

One major impediment to renewable development in many power systems, especially in the US, is the fact that most of the prime renewable resources are geographically distant from load centers. For example, DOE (2008) examines the implications of 20% of the US's energy being provided by wind by 2030 and shows that approximately 30 million MW-miles of new transmission lines would be needed to deliver wind energy to loads. In addition to the usual challenges associated with siting transmission lines, the sizing of the individual transmission lines is a non-trivial issue. Consider, as a simple example, a radial line connecting a single wind generator to a load center. The fundamental issue is that a high-capacity transmission line would often be underutilized when the output of the wind generator is low. A low-capacity transmission line, on the other hand, would result in the output of the wind generator being curtailed when its output is high. Thus the economics of wind development is complicated by either needing to overinvest in transmission to increase the amount of energy sold, or underinvest in transmission to reduce total capital costs. Energy storage that is co-located with the wind generator could be used to level the output of the joint wind and energy storage plant and reduce the amount of transmission capacity needed to deliver energy to the load center. Cavallo (1995); LCRA (2003); Denholm et al. (2005); DeCarolis and Keith (2006); Succar et al. (2006); Greenblatt et al. (2007); Denholm and Sioshansi (2009) examine this use of energy storage, and show that depending upon capital costs, wind patterns, and price patterns of the market in question, energy storage could be an economic alternative to transmission capacity for wind development. These analyses show, importantly, that the profit-maximizing mix of transmission and energy storage for a given wind generator size is not the same in different markets, highlighting the fact that this storage application will generally be quite site-specific.

The analysis of this energy storage application has focused on wind, mainly due to the fact that it is the most mature renewable technology. Many other renewables, such as CSP, tidal, and wave energy, may face similar issues, depending on the location of the prime resources relative to loads. Some other renewables, such as solar PV, will likely not encounter transmission-related issues. In the case of PV, since most installations are currently placed on buildings and PV generation is used to reduce building net loads, there will likely be no additional transmission capacity required in order to integrate PV into power systems.

4. Research and Policy Questions

Although a number of potential applications of energy storage, beyond providing an alternative to peaking capacity, have been identified, questions remain regarding the total social value of these uses and how policy and other decisions can affect this. Estimating the value of energy storage is confounded by the fact that many of the applications are very specific to the site or power system under consideration. Moreover, in some cases the averted cost or improved efficiency brought about by the energy storage is difficult (if at all possible) to quantify, since the requisite information is not provided by the market or otherwise difficult to estimate. This market limitation can make it difficult to justify, much less even identify, an investment in energy storage for an application that may be economic. For instance, since most power quality-related ancillary services are not priced in the market, the lack of transparent cost information may be an impediment to using energy storage for power quality-related applications. Similarly, because LMPs are generally not calculated at the distribution-system level, the market does not provide price information for distribution- related applications of energy storage.

These examples, and others, suggest that for some storage applications to become commercially viable in a restructured market environment, new market products may need to be developed. In other cases, regulated or other incumbents that currently provide the service in question may have an incentive to invest in storage as an alternative. For instance, a utility, generator, or LSE that provides power quality-related services in its service territory may better know the cost of providing these services and the benefits of using storage for this application. If such a firm deems storage an economically viable alternative to present practice, it may invest in storage. In such a case, storage use would have been spurred by reliability standards set by regulatory bodies as opposed to through an indirect market-or price-based mechanism. However, given the fact that some electricity market incumbents are viewed as being risk-averse in making investment decisions (for instance, Denholm et al. (2010) attribute the lack of energy storage investment in the 1980's and 1990's, in part, to the perceived risk aversion of utilities), these firms may not embrace technologies that they view as being relatively uncertain or unknown. On the other hand, the development of a NaS battery for distribution-related applications by AEP shows that utilities can be receptive to innovative uses of energy storage. Another complication in determining the full value of energy storage is that most storage analyses have, to a large extent, focused on a single use of energy storage by a single entity. This 'piecemeal' analysis of energy storage neglects the possibility of storage of being used for multiple applications, and that these applications may interact with one another.

For example, Denholm and Sioshansi (2009) examine the use of energy storage to reduce transmission requirements for a wind generator and for generation shifting. In this case the value of these two uses is subadditive, since the use of storage for arbitrage is constrained by the shared transmission line with the wind generator. Moreover, the storage in this example could potentially be used for other applications such as capacity deferral or ancillary services. To the extent that these uses of the storage could compete for transmission capacity with the wind plant and energy arbitrage activities or could require that more energy be kept in storage, the value of these other applications will generally not be additive either. As another example, the technique Tuohy and O'Malley (2009) use to estimate the capacity value of energy storage in a power system with high wind penetrations (which is described in section 3.1.2) may underestimate the capacity value of storage, since a storage operator that is concerned about capacity payments may keep more energy in storage during high-load periods than it would if it is minimizing system dispatch costs. These two examples underscore the fact that while many potential storage applications have been identified, storage could be put to multiple uses. Quantifying the value of and interactions between multiple applications will be important for future storage development, especially given the fact that many analyses show that the high capital costs of modern storage devices cannot be justified on the basis of a single storage application alone. Generally speaking, valid techniques to estimate multiple storage applications have not been developed, and this is an area needing future research and study. In other cases, storage that is used for one application could have unintended or incidental effects related to another application. In some instances this incidental application will affect an entity other than the storage owner, and externality-related market failures can arise.

For example, depending on the relationship between the load at the distribution and power system levels, energy storage that is built to relieve a distribution constraint can have negative or positive effects related to generation shifting. If the distribution-level peak is coincident with the system peak, then this use of storage will provide generation shifting benefits as well, since the storage device will be discharged during the system peak. If, on the other hand, the storage is used to serve PHEV or electric vehicle charging loads overnight that would otherwise overload a distribution-level transformer, then this use of energy storage would provide a generation shifting-related cost, since high-cost energy would be used to serve an overnight load. In this case the costs and benefits of storage use accrue to different entities and the net social benefits of storage use, which would consist of the averted cost of a distribution upgrade less the cost of storage and generation shifting, may be negative. Depending on some market design and policy parameters, the potential storage owner may or may not internalize the generation-related cost impacts in its storage investment and use decision, which could yield an inefficient outcome. For example, if a group of customers who pay a time-invariant electricity tariff are considering investing in a shared battery for PHEV charging purposes, the generation shifting cost of their storage use would not be included in the private benefit of storage. If, on the other hand, these customers pay a time-variant tariff then the relatively high cost of energy used for PHEV charging would factor into their decision.

Energy storage can also present externality issues that cannot easily be mitigated through pricing mechanisms or small market corrections. For example, Sioshansi et al. (2009) examine the arbitrage value of large-scale energy storage devices in the PJM market. Because large-scale energy storage will tend to increase the price of energy when it is charged and decrease the price of energy when it is discharged, the arbitrage value of energy storage will be decreasing in the size of the storage device. Their estimates show that 1 GW of energy storage will decrease the arbitrage value of energy storage (on a per kW basis) by between 10 and 20% compared to small price-taking energy storage that does not affect the energy price[10].

Their results show, however, that this use of storage will have external welfare effects. Consumer energy costs will tend to decrease, because while off-peak energy prices are increased when storage is charged, on-peak energy prices are decreased and this price decrease is applied to a larger quantity.

[10] The range of values comes from the fact that they examine several years worth of market data. They show that in earlier years, when the PJM market was smaller, 1 GW of energy storage would be relatively large compared to the market and would have a greater price effect. Thus, these years saw the value of storage decreased by more compared to the price-taking case. In later years, when the PJM market had expanded to include some neighboring control areas, 1 GW was relatively smaller compared to the market and would have had a smaller price effect, thus its arbitrage value would have been decreased by less compared to the price-taking case.

Generator profits will also decrease, because the profit decrease during on-peak periods when the price of energy price is suppressed and generator energy sales are reduced outweighs the profit increase during off-peak periods when the price and volume of sales increase. Moreover, their results show that these two price effects yield a net gain—the increase in consumer welfare outweighs generator profit losses. However, because the storage owner only captures the arbitrage value as opposed to the total social value of storage, which consists of the sum of the arbitrage value and the net consumer and producer welfare gain, this storage owner will likely underuse storage compared to the welfare maximum. Indeed, since the arbitrage value of storage is decreasing in its size, it may also underinvest in storage. Sioshansi et al. (2009) posit that contract or market mechanisms, that price these external benefits, may be needed to ensure that welfare-maximizing amounts of storage are built by a private investor.

Sioshansi (2010b) extends this analysis by examining the incentives of a merchant storage operator using large-scale energy storage solely for arbitrage purposes and shows that while there are welfare losses compared to a welfare maximizer, a merchant storage operator yields the smallest surplus losses compared to the alternatives of energy storage owned by a generator or an LSE[11]. Indeed, their results show that because generators and LSEs would use storage to maximize the sum of arbitrage profits and either producer or consumer surplus gains, respectively, they would tend to have perverse storage use incentives. Generators, for instance, would tend to underuse storage compared to the welfare maximum since storage use reduces producer welfare, whereas LSEs would overuse it since it increases consumer surplus. These results suggest that in some cases the market may be able to yield a second-best outcome, without the need for added complex market mechanisms. For instance, since storage use by a merchant storage operator would yield relatively low efficiency losses compared to the alternatives, existing market structures may be sufficient to signal the need for many storage applications. On the other hand, these potential welfare losses also suggest that storage use or investment by some entities may require closer scrutiny or attention on the part of regulators or policymakers. For instance, since LSEs have incentives to overuse energy storage resulting in social welfare losses[12], they may also have incentives to overinvest in energy storage relative to merchant storage operators or the welfare maximum.

Similarly, Sioshansi (2010a) examines the use of energy storage to increase the value of energy produced by a wind generator. As discussed in section 3.5.1, wind suffers from the fact that energy prices will tend to be negatively correlated with wind availability. This is because conventional generators will be less able to exercise market power and drive up energy prices during periods with high wind availability, since there will be less demand for conventional energy. Sioshansi (2010a) shows that energy storage can increase the value of wind energy by shifting generation from hours in which the energy price would be unduly suppressed to higher-priced hours. This analysis shows, however, that this use of storage will result in consumer and conventional generator welfare losses. Moreover, the consumer and conventional generator surplus losses are typically more than twice the increase in the wind generator's profits, showing that while this use of storage will make wind generation more economic, it will yield a socially undesirable outcome[13].

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[11] Sioshansi (2010b) considers the case of a consumer that owns energy storage and is concerned with maximizing the sum of arbitrage profits and consumer surplus gains. He argues that since it may be impractical for individual consumers to invest in and use energy storage for these purposes, an LSE that is concerned with reducing the cost of serving its customers could be a proxy for the consumer case. We follow this assumption in our discussion of LSEs owning storage.

[12] Sioshansi (2010b) shows that in some cases, the producer profit losses that result from storage use by an LSE can be an order of magnitude greater than the associated consumer welfare gains.

[13] To give a sense of the scale of these profit and welfare changes, his results show that energy storage can increase the annual profit of a 10 GW wind generator by up to $30 per kW of storage capacity, but can decrease the sum of consumer and conventional generator welfare by up to $138 per kW of storage capacity.

These examples emphasize the fact that some level of oversight regarding storage investment, especially for large-scale installations, may be needed due to these types of external effects of storage. Some applications of energy storage will also likely introduce network-type externalities that can complicate decisions such as where within a network energy storage should be sited. For instance, energy storage could be co-located with a wind or other renewable generator to reduce the transmission capacity necessary to deliver renewable generation to load centers. On the other hand, co-locating energy storage with the wind generator can constrain the ability of storage to provide other, potentially more valuable services. Energy storage that is sited at a load center could, for instance, reduce variability in total renewable generation and provide capacity firming services to the system as a whole. Although storage investment decisions will, in principle, be made on the basis of market signals conveyed in LMPs, the resulting decisions may be suboptimal from a social welfare standpoint. Sauma and Oren (2005, 2007, 2009) use simple examples to demonstrate that generators can make transmission investment decisions on the basis of LMPs that yield a net social welfare reduction. They attribute this result to the fact that network congestion is essentially a market failure and can provide perverse incentives to firms in a constrained transmission network. Although the issue of storage siting and the effect of network congestion has not yet been studied in detail, it is not clear whether market-driven decisions will yield a socially optimal outcome or not. Since some uses of energy storage, especially at large scales, can affect LMPs and power flows within a T&D network, it is not inconceivable that market behavior would be suboptimal. This is clearly an area of storage-related research that will require further examination.

5. Conclusions

This paper presents a survey of the history of energy storage development in the US and its potential future. We discuss many potential uses of energy storage beyond providing utilities with an alternative to building peaking capacity. In many cases, these new uses of energy storage stem from recent developments in the electricity industry, including market restructuring and the push for higher penetrations of renewables. The market potential of energy storage has also been aided by the fact that generation costs and the capital costs of traditional electricity technologies, such as generators, transmission, and distribution have risen. Moreover, recent research has identified many novel applications for energy storage beyond the traditional role afforded it. As a result of these analytic and technology advances, many demonstration projects have been built or are underway.

Despite these positive developments, many questions surround the future of energy storage. Investment in most storage technologies is difficult to justify, given the high capital costs of technologies that are currently available. As such, the question of how to optimally put storage to multiple uses and what the combined value of these uses would be is an important and largely unaddressed question. Due to market failures or limitations, some energy storage applications may not be viable from an ‘unregulated’ asset. For instance, because energy is not priced at the distribution level and most power quality-related services are not priced at all, distribution and power quality-related storage applications may only be feasibly provided by entities that are given a regulatory mandate to provide these services to the power system. On the other hand, if energy storage becomes a viable alternative to providing power quality-related services, the entrance of competitors to current incumbents may make markets for these services viable. In other cases, market designs currently hamper the ability of energy storage to provide some services, for instance relating to the treatment of regulation services as a single or two market products. In other cases, because certain energy storage applications can create massive and disruptive effects on other market stakeholders, there may be need for regulatory oversight of storage investment and use. It should be noted that our discussion has only present a few examples to highlight these issues, and that these examples are by no means comprehensive.

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