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# Estimating the Value of Electricity Storage: Some Size, Location, and Market Structure Issues

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## Introduction

The purpose of this paper is to better understand some of the potential benefits of electricity storage, particularly those associated with competitive wholesale power markets such as PJM.[1] Electricity storage devices have the potential to provide significant benefits through reduced energy costs to end users; improved utilization of the existing generation, transmission and distributions assets; as well as associated benefits from deferred capital improvements and/or additions. Additional benefits stem from its potential to firm up the output of intermittent resources, by providing a partial hedge and dampening effect against high natural gas prices and increased price volatility and by rendering the exercise of supplier market power more difficult. Many of these factors also contribute more generally to improved security and reliability, including risk mitigation against market disruptions.[2] These potential benefits must be weighed against the costs of such storage devices. We discuss some of the implications of ownership structure and market rules on the ability to appropriate the benefits associated with storage devices, and to what extent that makes construction of storage devices feasible if societal benefits exceed societal costs. Increasing the total amount of storage in a given electricity system can lead to substantial shifts in the size and nature of benefits between the various stakeholders – and these need to be considered from both the short-term and longer-term perspective.

In this paper, we give particular emphasis to the impact on the economic value of electricity storage due to: (i) the significant increases in the price of natural gas over the past few years – and the related issue of how location more generally affects arbitrage value, (ii) the impact of changes in the total amount of storage in a given electricity system, and (iii) the effect of ownership structure/market structure and rules on the division of benefits. These three factors are important to any real investment decision (e.g., whether to build, where to build, how much to build).

This paper is intended to contribute to defining a framework for such analysis and provide some preliminary results and insights.[3]

## Arbitrage Value of Small-scale Storage and the Impact of Rising Natural Gas Prices and Locational Considerations

A storage device captures arbitrage value by using cheaper off-peak power and then selling higher-priced power during peak hours. A number of earlier studies have looked at the arbitrage value of small electricity storage devices in the United States. Despite recent increases in the arbitrage value of electricity storage, these studies have generally found that arbitrage alone is not sufficient to justify building such a device.[4]

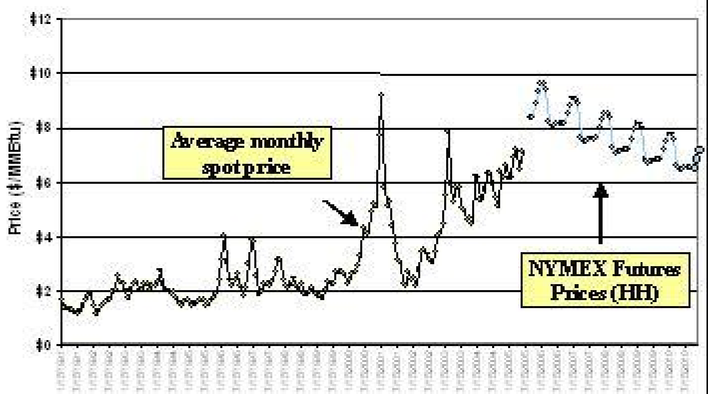
A number of methods can be used to bound the economic arbitrage value of storage. Simple operational rules provide a lower bound, while (monthly) price duration curves – where the highest hourly prices are mapped to the lowest priced ($1/\eta$) hours – provide an upper bound. For PJM, in 2002, these techniques bounded the value

[1] This paper is based on a presentation for the EESAT 2005 conference in San Francisco on October 17, 2005.
[2] Ancillary services are another source of value (though usually as alternatives rather than additions to arbitrage). These can be particularly attractive because they value capacity over energy, at least for limited amounts of storage (also see Footnote 3).
[3] Subject to funding considerations, it is hoped to expand this preliminary work into a larger study that will examine the value of various benefits at a more local level within a specific region, as well as more generally across a number of regions.
[4] Devices are often considered to be so small, in that their operation does not collapse or substantially affect the peak-off-peak prices. See e.g., Frank Graves, Thomas Jenkin, and Dean Murphy, *Capturing the value of storage in the energy and reserve markets*, Electrical Energy Storage – Applications and Technologies conference in Orlando, Florida, September 18, 2000 (EESAT 2000).

of a typical storage device at $50 to $75/kW-yr.[5] Peak/off-peak price differences and price volatility are key drivers in determining the value of arbitrage. Other factors include the efficiency of the device, how it is operated – including degree of "perfect foresight" – and device size constraints.

Between 2002 and 2004, the price of natural gas has risen sharply from typically around $2/MMBtu to $4/MMBtu in 2002 (at Henry Hub) to an average of more than $5/MMBtu in 2003 and in 2004.[6] Because the value of storage is driven by the difference between peak and off-peak prices – which, in turn, will reflect both the fuel mix in the region and the underlying fuel prices – the increase in the potential arbitrage value of storage in PJM in 2003, while significant, was not nearly as high as the relative increase in natural gas prices (though the upper bound reached $100/kW-yr, or more for an unconstrained device.)[7] To understand this, it is useful to consider the different impact of a $2/MMBtu increase in price for a gas generator, a storage device, and renewable energy (wind or solar) (see Figure 1).[8]

**Figure 1: Natural Gas Prices (Henry Hub) $/MMBtu**




**Relative impact of $2/MMBtu increase in natural gas price**

**Gas Generation**
Cost increase of $20/MWh (for a 10,000 Btu/kWh heat rate) – Similar increase in power prices when gas on margin

**Storage**
Benefits from increased prices of peaking power during discharge. Off-set depends on cost of storage's "fuel" "off-peak power (next page)

**Renewable (Solar, Wind)**
Captures most of the benefit of increased power prices because "fuel costs" are zero

Higher gas prices push power prices up at peak times when – as is common – gas is on the margin. However, conventional gas-fired generation on the margin does not profit more under such scenarios because it is still on the margin, i.e., the cost of fuel has increased. By contrast, a storage device's fuel is "off-peak" power. This will be much less affected by the price of gas – though how much less depends on the off-peak fuel mix. If the off-peak charging hours are driven by nuclear or hydro, storage will receive the complete benefit from the rise in gas prices. Even if gas is on the margin for some of the off-peak hours, rising gas prices will increase the

[5] Optimization techniques that allow for physical device constraints and have perfect foresight will fall between these boundaries, but also tend to be overoptimistic. Efficiency, $\eta$ of 80% was used for arbitrage estimates. All the PJM power price and load data used in this analysis comes from www.pjm.com

[6] With natural gas prices at Henry Hub (and associated NYMEX futures prices) continuing to increase in 2005 with spot and forward prices often well in excess of $6/MMBu. Very recently (presumably and hopefully transient) $10+/MMBtu pricing has been observed resulting largely from the damage (physical and perhaps also psychological) caused by recent hurricanes in the Gulf Coast. We focus on 2004, because we are interested in understanding potentially sustainable value, and these natural gas prices are at least anchored to some degree by potential economic costs of LNG in the United States (though, admittedly, this assumes a reasonable competitive market – which is arguably not the case for the crude oil) – though see also discussion of value from risk mitigation against market disruptions.

[7] Depending on assumptions about the device's efficiency, costs, and other factors.

[8] The delivered price of gas will generally be higher in PJM – though strongly correlated to Henry Hub prices – due to a "basis" differential that reflects additional transportation costs from major gas sources, such as the Gulf and Western Canada. Gas transmission constraints can lead to increased basis differentials and volatility.

value of storage. This is because a $1/Mcf increase in gas prices will lift the peak price more than the off-peak price, due to the better heat rate/efficiency of the off-peak units.

Thus, storage will be more valuable in regions where large amounts of nuclear power, hydro and (to a lesser degree) coal are available for off-peak power generation (see Figure 2).[9] Because higher peak power prices tend to increase the arbitrage value for storage, the distance from gas sources can also be a factor because of locational gas price differences (known as "basis" differentials) reflecting implicit transportation (and/or gas storage) costs.

**Figure 2: Impact on Relative Change in Value of Storage with Increase in Gas Price**
**(By Off-Peak Fuel Type (and hence Region)) – Impact of moving from $4 to $6/MMBtu**

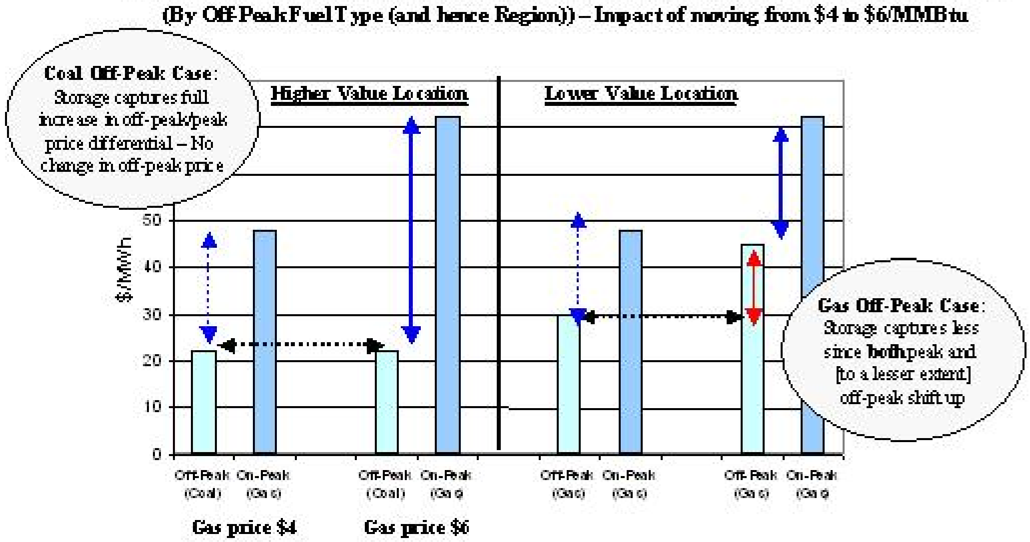
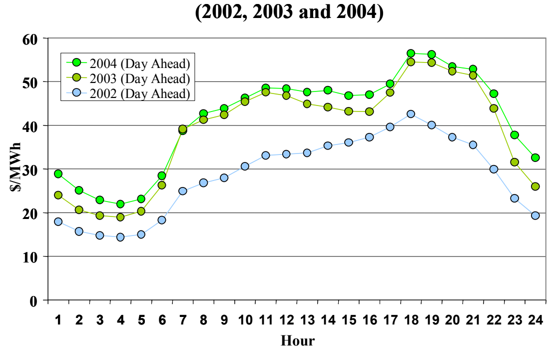
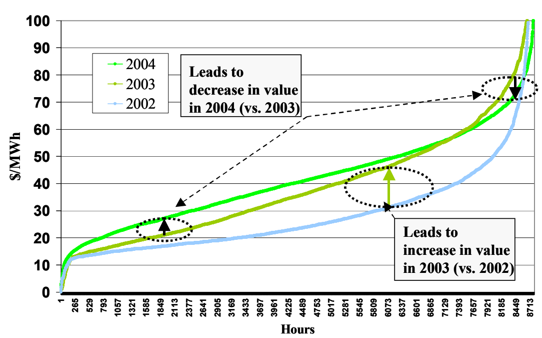



Figure 3 shows the changes in PJM prices and price-duration curves for 2002, 2003, and 2004 used for a "simple rule" and price-duration curve analysis of storage arbitrage value for 2002, 2003, and 2004.[10]

**Figure 3: Average Hourly Prices (LMP) for PJM (2002, 2003 and 2004)**




**Price Duration Curves for PJM (2002, 2003 and 2004)**




[9] Figure 2 simplifies the situation, because it assumes coal prices are unaffected by changes in the price of gas. This may not be the case – e.g., see discussion of reasons why the value storage fell in 2004 in PJM.
[10] A very "simple rule" could discharge into the highest priced 8 hours and charge during the lowest priced 10 hours on a daily basis throughout the year (see Figure 3(a)). In the presentation, more sophisticated "simple rules" were used where different operating behavior for weekends vs. weekdays and seasonal effects were assumed. Price duration curve estimates were done on a monthly and two-weekly basis.

The increase in the value of storage between 2002 and 2003 can be clearly linked to the significant increase in power prices during the peak periods – which is to be expected given the large increase in natural gas prices in 2003. Despite further increases in the average price of natural gas in 2004, the value of storage actually fell relative to 2003. There are a number factors contributing to this, including a reduction in gas price volatility, discussed below. Principally, while peak prices increased slightly on average (as did the price of natural gas), average off-peak power prices increased significantly and the occurrence of price extremes (and volatility) decreased (see Figure 3). While these observations can explain the decrease in storage value in 2004, they do not fully explain why off-peak prices increased. More work needs to be done in this area, but there are a number of factors that are consistent with these changes. Coal prices in PJM rose substantially by more than 20% between 2003 and 2004,[11] and this would be expected to increase off-peak prices and hence reduce the value of storage. More generally, and related, is the fact that the "game" keeps changing. In 2004, in particular, the size of the PJM market increased significantly (both in area covered and MW added) – and, consequently this would be expected to lead to changes in demand profiles and generation mix, both of which would be expected to affect off-peak prices even without a change in gas prices.[12]

**The Impact of Storage Amount on the Value of Storage**

As the amount of storage in a system increases, the arbitrage value on a $/kW-yr basis will decrease as increasing amounts of peak load are shifted to off-peak periods, resulting in higher off-peak and lower on-peak prices, thus reducing the marginal arbitrage value of an extra unit of storage. The net result will be a flattening of both the hourly load profile and the hourly price profile for each day. Theoretically, entry by storage devices should occur until all profitable opportunities to buy cheap off-peak and sell high on-peak are arbitraged away.[13] While the arbitrage value is, therefore, reduced with increasing amounts of storage in a given system, there are a number of significant benefits gained as a result of the load-shifting impact of the storage device. These include:

1. Increased Consumer Surplus: Reduced prices to end users because of significant shifts in consumer surplus from producer surplus.
2. Deferred T&D: Increased societal benefits because of improved utilization of the transmission system and the related deferred need to build more transmission.[14]

Figure 4 shows the shifts of surplus when the amount of storage results in changing peak and off-peak prices.[15] The increase in consumer surplus while discharging during an on-peak period comes from lower on-peak prices at the expense of the producers' surplus. This net surplus shift generally exceeds the shift in the opposite direction that results during charging because of increasing off-peak prices, leading to a net gain to the consumer and loss to the producer. While such a shift leads to lower averages prices for end users, careful attention must be paid to the impact of a flattening price profile on generators' ability to recover their costs in a perfectly competitive wholesale market for electricity and resulting long-run impacts on generation entry and exit. On the other hand, substantial amounts of storage would also make the exercise of supplier market power more difficult. Storage would essentially make on-peak demand more elastic, thus increasing the cost of exercising market power and thus reducing the benefits of doing so. The net impact of both tendencies on the societal desirability for large amounts of storage in a given electrical system will depend largely on the specifics of the system considered – fuel mix, demand profiles, supply-demand mix, market structure.[16] There are also further related risk-management benefits, in that storage can mitigate against potential adverse impacts of market failure and market disruptions.[17] Finally, Figure 4 also shows that there is a reduction in the arbitrage revenue (partly offset by increased charging costs) that should benefit consumers (at least in the short run).

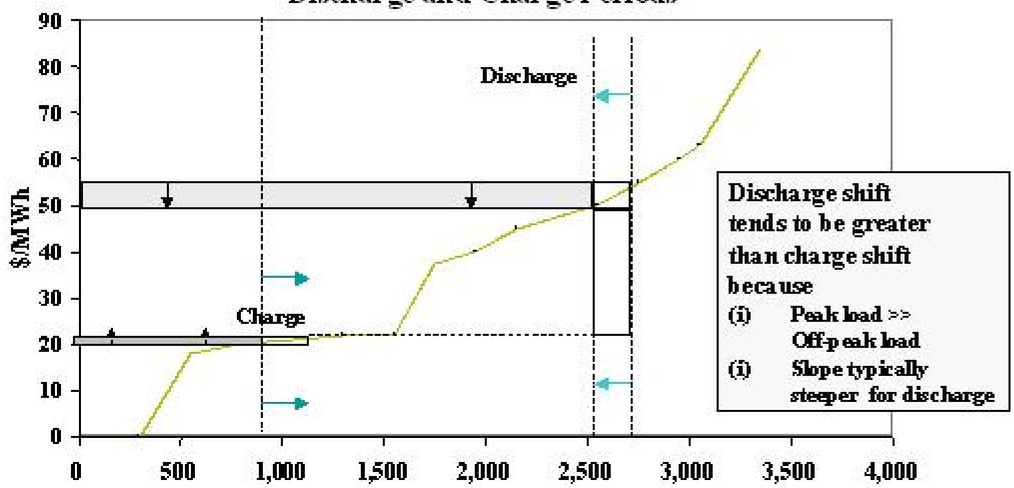
[11] PJM 2004 Market Monitoring Report.
[12] Other potential effects are competitiveness of the market/premiums and the weather.
[13] Though this would have to include covering the capital cost of the device and obtaining a reasonable return on an expected basis – something not considered feasible from arbitrage-only considerations.
[14] Also increased societal benefits because of improved utilization of the generation system, and the related deferred need to more generation.
[15] Using an illustrative generation supply curve and assuming inelastic demand.
[16] And hence needs to be informed by detailed empirical analysis we have not performed at this point.
[17] Surplus shift arguments tend to assume that the markets are in equilibrium. In the real world, there may be real value from a risk-management perspective in using such devices to mitigate the impact of market failure (e.g.,

The non-arbitrage-related benefits are less controversial because they are additive values to society: It is almost self-evidently good that load shifting leads to the more efficient utilization of existing transmission and generation assets. [18] However, the value of storage from this perspective varies widely:

- For an underutilized line, there is little economic value;
- For a full line, it has value immediately against future load growth;
- For an "overfull" line device, it can also relieve "congestion" cost.

Moreover, the cost – as distinct from value – of building transmission can also vary widely on a per-MW basis, depending on how long the line needs to be. More generally, the value of storage in providing this peak-load shifting service needs to be set against the cost of the next-best alternative, including potential transmission upgrades and/or additions, the use of distributed generation and/or load management, or some combination of the above, including storage.[19]

**Figure 4: Shifts in Consumer and Producer Surplus during Storage Discharge and Charge Periods**




**Note**: Charge increased by 1/ η to reflect effect of efficient loss during charge discharge process – Alternatively same MW for charging and discharging but 1/ η times the discharge period

**Ownership and Market Structure**

One of the common complaints and/or concerns of potential investors in storage devices is that while storage generates a variety of value streams, these value streams are (i) either not paid for and/or (ii) paid to the wrong person. Moreover, different market participants (e.g., private investor, utility generator, transmission operator/ISO, and customer) have very different interests and incentives.

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California power prices without price caps) or market disruptions (e.g. recent hurricanes). For example, in the case of increasing gas prices because of a severe supply disruption – such as experienced recently due to hurricanes in the Gulf, large amounts of storage would be expected to reduce peak load, peak prices, and gas use (and prices). The benefits of reduced price increases would benefit society by lowering prices to consumers (relative to what they would have otherwise have been) and limit "windfall" gains to producers.

[18] Some studies put the value of forgone transmission build/upgrades due to storage at $400/kW in some instances; though, as these authors note, potential value is extremely site specific. See e.g. Iannucci, Joe and Eyers, Jim, *Technical and Market Aspects of Innovative Storage Opportunities,* DOE Annual Peer Review. November 20, 2002.

[19] This paper has focused on the value of storage and, in many senses, has been deliberately agnostic about what particular technology might provide large-scale storage. One interesting avenue currently being considered by some is the use of vehicle-to-grid hybrid-electric vehicles – though the initial focus of some of this analysis has been on the provision of ancillary services.

For example, a private investor building a small device for arbitrage may result in few short-term benefits for customers as the arbitrage value is captured by the owner of the storage device. However, as discussed at the beginning of the paper, arbitrage value alone may not be sufficient to justify private investment in storage; but a private investor will find it difficult to capture additional benefits provided by storage such as deferred investments in transmission. In a market like PJM, where a significant percentage of transactions clear at the spot market price, a private investor may not have the incentive to build the socially optimal amount of storage, because this may lead to peak load (and price) shifting, which will literally "kill the golden goose." The incentives for a Genco, i.e. a company with a portfolio of power plants, to build (and subsequently operate) large amounts of storage could be even worse. If a Genco with no market power built a large amount of storage, it would lower prices received by all of its generation assets on-peak more than it would increase its revenues off-peak.[20] If it had market power prior to building a large amount of storage, its ability to profitably exercise this market power would be curbed by the opposing incentives created from its storage facilities, much like Gencos with load-serving obligations have lower incentives to exercise market power than those who do not. So while from society's perspective it may be desirable for a Genco to build large amounts of storage, the incentives for a Genco to do so are likely significantly lower. The incentives are significantly different for a transmission operator or ISO, where the storage device could be considered a regulated asset. Both arbitrage benefits and transmission deferral benefits could be partly passed on to end users (beyond revenues necessary to pay for the device (which will depend partly on whether the entity is a not-for-profit or profit-driven entity). The Transco/ISO would also potentially see load- and peak-price shifting as desirable and have no regrets about lost arbitrage. In its mix of options to operate wholesale markets and transmission systems, storage could be recognized as a lower-cost potential alternative to transmission expansion, reliability enhancer, or reserve provider and may actually lower the overall cost of providing the coordinating functions provided by the ISO/Transco. This is an area that could benefit from further analysis.

## Summary

The approach discussed here is intended to contribute to providing a framework for thinking about a number of storage-related issues. Our analysis was considerably simplified by "collapsing" and using a representative price for large region. A more detailed study of PJM (and other regions) would need to work at a "lower level" to take account of regional differences, locational marginal prices, congestion costs, and other factors. Large amounts of storage might turn out to be quite small within this context. Some key insights, many of which are already generally known, are:

- Value of storage from arbitrage has increased in PJM since 2002, because of increases in natural gas prices – with recent power prices supporting $50 to $70/kW-yr, or more in PJM:
  - Decrease in 2004 vs. 2003 may be partly due to rises in coal prices in PJM in 2004.

- Value drivers of storage (not all independent) include:
  - Increased gas price volatility and, hence, power price volatility
  - Increased gas prices and, hence, increased peak power prices (when gas is on the margin)
  - Increased distance from a gas supply source (and higher gas prices due to basis)
  - Off-peak load served by nuclear, hydro, and (to a lesser degree) coal
  - Transmission congestion.

- Large amounts of storage present challenges and opportunities relative to small amounts
  - Reduced arbitrage to private owner
  - Large shifts in consumer and producer surplus leading to lower prices to consumers – at least in the short-term. Also short-term risk management benefits from mitigation against market disruption and market failure
  - Better utilization of existing T&D can be of significant value e.g., against deferred transmission – but must look at next-best alternative to assess true economic value.

- Value capture depends on ownership and market structure. Incentives for private investor vs. Transco/ISO are very different.

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[20] This assumes an unregulated Genco.