A Comparative Analysis of the Value of Pure and Hybrid Electricity Storage☆

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Abstract

Significant natural gas and electricity price variation and volatility, especially during the past few years, raise questions about understanding the value drivers behind electricity storage. The impact of these drivers for pure storage (such as pumped hydroelectric storage) and compressed air energy storage (CAES) are different and in this paper we explore these differences in operation and net revenue over a variety of timescales. We also consider the arbitrage value that is attainable in practice and explain why simple forecasting techniques based on historical data will generally be less successful for CAES. The breakeven cost of storage and how this can depend on regulatory treatment of storage and market structure is also considered.

Keywords: Energy storage, arbitrage, natural gas prices, investment decisions
JEL: Q4

1. Introduction

The emergence of wholesale electricity markets together with significant changes in prices and price volatility in these markets have increased interest in the potential opportunities for electricity storage to take advantage of differences in on- and off-peak electricity prices, as well as other sources of value. Sioshansi et al. (2009) examined the value of arbitrage in PJM for a pure electricity storage device from 2002 to 2007, a period that was generally characterized by increases in natural gas and electricity prices and significant price volatility. Sioshansi et al. (2009) also examined qualitatively the impact of natural gas, load, and other factors on the value of storage and the predictability of energy arbitrage value using historical data and price patterns. Continued recent volatility in natural gas and electricity prices along with renewed interest in storage has motivated us to better-understand the drivers of storage value, and in particular how it differs between a pure storage device, such as pumped hydroelectric storage (PHS), and compressed air energy storage (CAES), which is a hybrid storage technology which uses both electricity (to compress air) and natural gas. This comparison is relevant because there is significant interest in both CAES and PHS, in particular with regard to their potential use in facilitating the integration of large amounts of renewables.

Deane et al. (2010) note that bulk energy storage is currently dominated by PHS, with about 20 GW in the U.S. and over 90 GW worldwide and that there is considerable interest in continued PHS development, both in new locations and through rebuilds and expansion of existing facilities. Succar and Williams (2008) also note that there is interest in developing CAES, which is often seen as the primary alternative to PHS for bulk storage. Given the potentially significant difference in capital costs, as well as the hybrid nature of

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CAES, it is valuable to examine the potential differences in operation, revenues, and profitability between the two technologies over a range of timescales.

The paper is organized as follows: section 2 first introduces the technical characteristics of pure storage and CAES devices and the optimization model used in our analysis. This section then examines the different operational characteristics and arbitrage value for pure storage and CAES devices that result from variations and trends in natural gas and electricity prices. This includes seasonal differences in electricity prices that result in significant differences in the absolute value and comparative value of CAES and pure storage over the years examined. Section 3 then considers the distribution of weekly value of net revenue using perfect foresight, and uses these and findings from section 2 to demonstrate and explain the relatively poor performance of simple forecasting operational rules for CAES compared to its success with pure storage. Section 4 compares the net value and return on investment of pure storage and CAES, based on arbitrage and other sources of value, while taking account of differences in capital costs. This section also comments on breakeven costs for CAES and pure storage and how it may vary significantly based on regulatory assumptions, market structure and ownership considerations. Section 5 summarizes some of the main findings of and concludes the paper.

2. Variation of Arbitrage Value of Electricity Storage

2.1. Background and Methodology

One of the best-understood and studied applications of energy storage is energy arbitrage that results from load shifting—using storage to buy low and sell high. This type of analysis generally assumes that the device is a price-taker—small enough that its charges and discharges do not affect the hourly price of electricity. It also often assumes perfect foresight of future hourly power prices. Examples of this type of analysis that have been applied to wholesale electricity markets include Graves et al. (1999); Walawalkar et al. (2007); and more recently Sioshansi et al. (2009) who also examined the impact of relaxing the perfect-foresight assumption.

With a pure storage device electricity is converted to another form of energy (e.g., potential energy in the case of PHS or electrochemical energy in the case of a battery) when the device is charged. When the device is discharged the stored energy is converted back to electrical energy. Regardless of the technology a storage device can be generically characterized by its output power capacity (in kW or MW), its energy capacity (typically given kWh or MWh), and a round-trip efficiency.[1] The energy capacity of a storage device is often rated by the number of hours of full power output, which is the convention used in this paper. As discussed by Denholm and Kulcinski (2004), the power and energy capacity and efficiency of storage devices can vary considerably. For instance, PHS and large batteries may store enough energy to accommodate a full day's on-peak demand period of eight hours, and in the case of PHS devices have been built with over 20 hours of discharge capacity. Adamson (2009) notes that there is considerable interest in new PHS in the U.S., with about 30 GW of new capacity proposed between 2006 and 2009.

An alternative to pure energy storage is CAES, which is a hybrid storage device requiring both electricity to compress air, and natural gas. CAES is based on conventional gas turbine technology and utilizes the potential energy of compressed air. Energy is stored by compressing air in an airtight (typically underground) storage vessel. The two existing plants use a solution-mined salt dome, but proposals include hard-rock and aquifer reservoirs. To extract the stored energy, compressed air is drawn from the storage cavern, heated, and then expanded through a high-pressure turbine that captures some of the energy in the compressed air. The air is then mixed with fuel and combusted, with the exhaust expanded through a low-pressure gas turbine connected to an electrical generator. CAES is considered a hybrid generation/storage system because it requires combustion in the gas turbine. A more detailed description of CAES is provided by Succar and Williams (2008).

[1] When considering or comparing energy storage devices for energy arbitrage it is important to evaluate the net ac-ac round-trip efficiency, also considering parasitic loads such as heating or cooling of batteries or power electronics.

In this section we first estimate the historical annual value of arbitrage for a price-taking storage device in PJM over the seven year period 2002 through 2008. PJM refers to the PJM Interconnection, a regional transmission organization serving 51 million people in the eastern U.S. It operates an hourly day-ahead and real-time hourly energy market, as well as other capacity, transmission, and ancillary service markets. For each year the hourly operation of the storage device is optimized over successive weeks using hourly day-ahead load-weighted marginal electricity price data obtained from PJM. The optimization is conducted one week at a time to allow for inter- and intra-day arbitrage opportunities, including greater charging over weekends since hourly electricity prices tend to be lower than during weekdays, and also to reflect the fact that a storage operator would not be realistically expected to make dispatch decisions in anticipation of hourly prices many weeks in the future. In order to ensure energy stored in the device at the end of each one-week period has 'carryover value,' each optimization is done with an eight-day planning horizon to determine the dispatch of each one-week period. Otherwise, the device would be fully discharged by the end of each one-week period, which would not reflect actual device operation.[2] For pure storage the base case device is initially assumed to have perfect foresight of future hourly electricity prices over each eight-day period, an 80% round-trip efficiency, and a variable operation and maintenance (VOM) cost of $1/MWh of generation. We also evaluate a 70%-efficient storage device, which together with the 80% case, covers the likely range of efficiencies of modern PHS plants, as described in ASCE (1993). This range of efficiencies also covers most of the range of utility-scale batteries likely to be used for energy arbitrage applications, as described in EPRI (2003). The value of arbitrage for each one-week period is summed over the year to provide annual arbitrage values on a $/kW-year basis.

The approach for CAES is similar, except that the round-trip efficiency of the device is modeled differently to reflect the hybrid nature of CAES. Our base assumption for the performance of CAES is an energy ratio (which measures kWh of electricity in per kWh of electricity out) of 0.7, a heat rate of 4200 BTU/kWh, and a VOM cost of $3/MWh of generation. We assume that the combustion turbine used when discharging has a minimum operating point that is 20% of its rated discharging capacity. Thus, for example, we assume that if a 250 MW CAES is discharging, it must discharge at least 50 MW.[3] We use daily Henry Hub natural gas prices for the cost of gas used by the CAES device. Because a CAES device has an energy ratio of 0.7, only 0.7 MWh of stored electric energy is needed to discharge 1 MWh of energy. Thus, a CAES device with eight hours of discharging capacity must charge at full capacity for only 5.6 hours. In contrast an 80%-efficient pure storage device must charge for 10 hours, and a 70%-efficient device must charge for 11.4 hours.[4]

2.2. Annual Variation in the Value of Pure storage and CAES

Figure 1 shows the annual arbitrage value of pure storage and CAES devices with several configurations (i.e. different device sizes and pure storage efficiencies) on a $/kW-year basis. There is considerable year-to-year variation, with the value of pure storage with 80% efficiency and 20 hours storage ranging from about $60/kW-year in 2002 to over $110/kW-year in 2005. The value of CAES is significantly less than pure storage, ranging from about $40/kW-year in 2002 to about $80/kW-year in 2007 and 2008.[5] Figure 1 also shows that the annual arbitrage value of an 80%-efficient pure storage device is always greater than CAES, though this is not always true for a 70%-efficient pure storage device. In the years evaluated, the arbitrage value of CAES is 60% to 83% that of an 80%-efficient device, and 76% to 105% that of a 70%-efficient

[2] See Sioshansi et al. (2009) for a more detailed discussion of the use of the carryover assumption.

[3] There have been no CAES plants built since 1992 and the actual performance of a modern CAES plant is unknown. Our performance assumptions are based on a range of estimates from sources including Succar and Williams (2008); Greenblatt et al. (2007); Denholm and Kulcinski (2004).

[4] We assume throughout our analysis that storage devices have the same charging and discharging power capacity, although, as Greenblatt et al. (2007) note, most modern storage technologies can be designed with different capacities, and this would be an interesting area for further work.

[5] This potentially underestimates the cost of CAES operations since the cost of natural gas in PJM often commands a premium of $0.50 to 2/MMBtu, or more due to transportation costs. Because a CAES operator is likely to choose a site that would minimize the natural gas transportation costs, we did not make any explicit assumptions about this cost premium. As a sensitivity, we examined a case in which natural gas has a $1/MMBtu transportation cost, which reduced the annual arbitrage value of CAES by between $6 and 13/kW-year.

device. The absolute premium is \$11 to 43/kW-year for an 80%-efficient device and -\$4 to 19/kW for a 70%-efficient device.

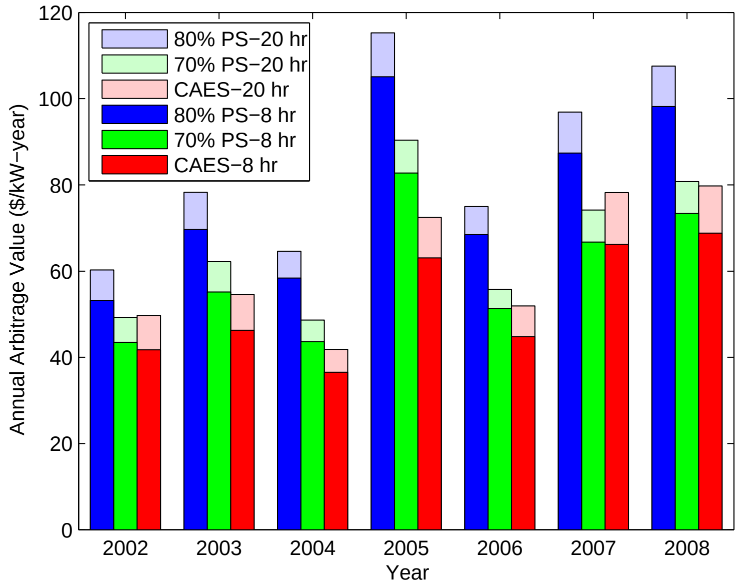

Figure 1: Annual arbitrage value for pure storage and CAES devices with eight and 20 hours of discharge capacity.

Variations in the value of pure storage and CAES are driven by the underlying differences in on- and off-peak electricity prices, as well as the cost of CAES operation due to natural gas. While some of these trends are observable on an annual basis, greater insight can be gained by examining the seasonal and weekly trends in electricity price, gas costs and storage value, and the resulting relationships between the value of pure storage and CAES.

2.3. Weekly and Seasonal Variation in the Value of Pure Storage and CAES

Figures 2 and 3 show the weekly arbitrage value of an 8-hour pure storage and CAES device over a 43-month period between June 2005 and December 2008, along with the difference in on- and off-peak weekly electricity prices (figure 2) and the average weekly price of natural gas (figure 3).[6] We focus on this period because the PJM service territory grew considerably in the years leading up to early 2005. Since the introduction of new generators and loads as the PJM footprint expanded could affect energy prices, we chose a period without any of these market expansions. These figures demonstrate the tremendous weekly volatility and clear seasonal effects. The average weekly value for the eight-hour 80%-efficient pure storage device is \$1.8/kW-week, with a range over this period of \$0.3 to 6.1/kW-week. For the CAES device is it is about 30% lower, averaging \$1.2/kW-week with a slightly wider range of -\$0.2 to 6.6/kW-week).[7] The volatility, as measured by the standard deviation, is 1.03 and 0.98 for pure storage and CAES, respectively. This is only an approximate measure of variation since the weekly and daily net revenue distributions are asymmetric, rather than normal, and positively skewed. When considering a 70%-efficient pure storage device the weekly value falls from \$1.8/kW-week to 1.4/kW-week, and a range of \$0.2-5.3/kW-week, which is much closer to the values observed for CAES.

[6] In both cases we need to decide on a representative measure of the weekly average. For on- and off-peak electricity prices we use the difference in the average daily top six peak hourly prices and the bottom eight hours. For natural gas it is simply the average daily value for the week.

[7] The negative value for CAES is not due to forecast error, since the model assumes perfect foresight in prices. The negative value results from energy purchases at the end of the week that are carried over to the next day, resulting in a net profit over the eight-day optimization period.

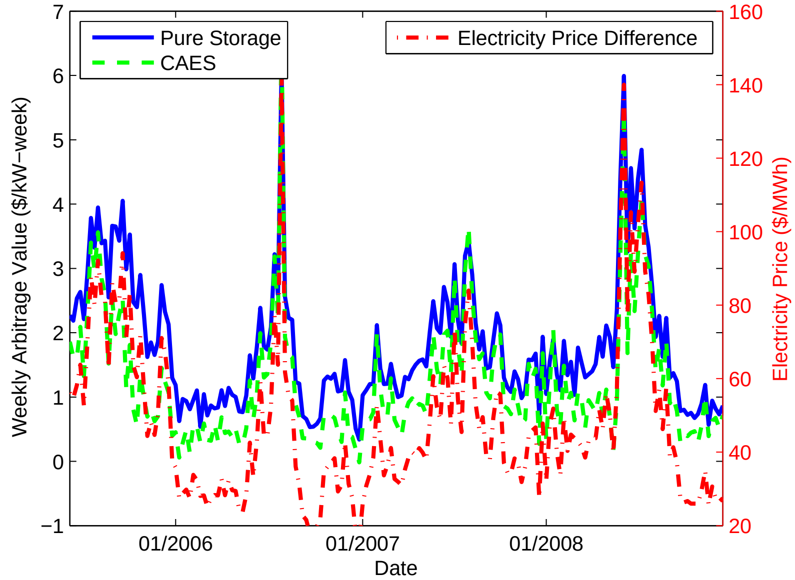

Figure 2: Weekly arbitrage value of pure storage and CAES and the average on- and off-peak electricity price difference.

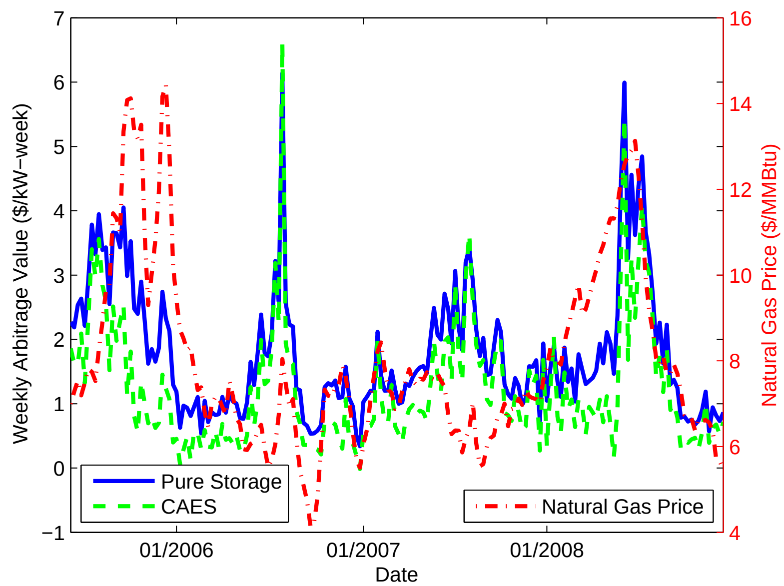

Figure 3: Weekly arbitrage value of pure storage and CAES and the average Henry Hub price of natural gas.

Figure2 shows significant seasonal trends in the weekly value of storage. The most obvious variation in storage value for both pure storage and CAES is driven by the difference in on- and off-peak electricity prices. The weekly values for both CAES and pure storage are generally greatest in each of the summer periods, which reflect greater loads during the summer—with weekly values during the summer commonly being a factor of two to three or more greater than those during the winter. This relationship is driven by the significant seasonal variation in load, and the strong underlying relationship between electricity prices and loads, as demonstrated by many analyses including Karakatsani and Bunn (2008).

While the weekly value of pure storage is driven almost exclusively by the on- and off-peak electricity price difference, the weekly value of CAES is also dependent on the cost of natural gas. The correlation between the value of pure storage and the on- and off-peak price difference is 0.99. In contrast, the corresponding correlation for CAES is reduced slightly to 0.93, which reflects the impact of natural gas prices on the value of CAES. Table 1 demonstrates these and other relationships by summarizing the cross-correlations between the value of pure storage and CAES and a number of market drivers, such as electricity and natural gas prices, over the same three and one half year period shown in figures 2, 3, and 4. Figure 3 is similar to figure 2, but includes the weekly average natural gas price. In general, there is a positive relationship between natural gas and on-peak electricity prices of 0.63, which reflects the fact that natural gas generation often sets the marginal price during on-peak periods. As a result, there is a positive correlation of 0.54 between the value of pure storage and the average natural gas price. The increase in on-peak electricity prices associated with increased natural gas costs also leads to an increase in the value of CAES with higher natural gas prices, despite its fuel use. The impact of the fuel use is to reduce the correlation between the value of CAES and natural gas prices to 0.26 compared to 0.54 for pure storage.

Table 1: Correlation of weekly value of storage and other weekly-averaged parameters.

	Natural Gas Price	Value of 80%-eff. 8-hour PS	Value of 8-hour CAES	On-peak elect. price	Off-peak elect. price	On-/off-peak elect. price diff.	Value prem. of 80%-eff. 8-hour PS above CAES	Value of 70%-eff. 8-hour PS
Natural Gas Price	1.00	0.54	0.26	0.63	0.46	0.58	0.80	0.52
Value of 80%-eff. 8-hour PS		1.00	0.93	0.92	0.29	0.99	0.31	1.00
Value of 8-hour CAES			1.00	0.89	0.34	0.93	-0.05	0.93
On-peak elect. price				1.00	0.64	0.95	0.21	0.90
Off-peak elect. price					1.00	0.36	-0.10	0.24
On-/off-peak elect. price diff.						1.00	0.30	0.98
Value prem. of 80%-eff. 8-hour PS above CAES							1.00	0.31

Table 1 also shows a strong correlation of 0.80 between natural gas prices and the premium in the value of an 80%-efficient pure storage device over CAES. This relationship can be seen in figure 4, which shows the premium in the weekly value of 80%- and 70%-efficient pure storage above the value of CAES, from the way the positive and negative week-to-week variation tend to move together. The higher natural gas prices in the summers of 2005 and 2007 result in a significant premium for pure storage compared to the other years evaluated. Figure 4 also shows that the average premium over CAES of a 70%-efficient device is reduced compared to the 80%-efficient device, as would be expected. This is also reflected by the reduction in table 1 of the correlation of the value premium of pure storage over CAES with natural gas prices from 0.80 for 80%-efficient pure storage to 0.58 for 70%-efficient. Figure 4 also shows that there are a few periods where CAES exceeds the value of an 80%-efficient pure storage device (indicated by a pure storage premium of ¡ \$0/kW-week), but the value of CAES exceeds that of a 70%-efficient device about 30% of the time.

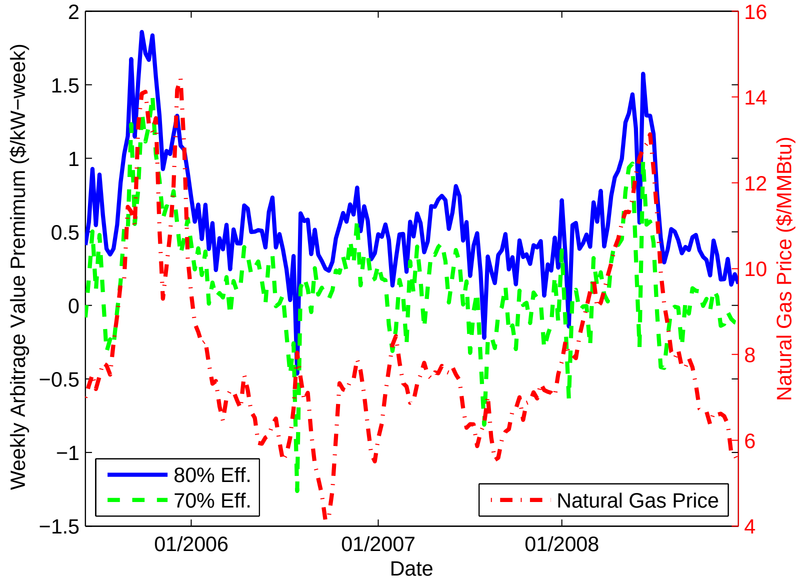

Figure 4: Weekly premium in the arbitrage value of pure storage over CAES and the weekly average Henry Hub price of natural gas.

2.4. Effects of Season and Electricity and Natural Gas Prices on Hourly Operations

Section 2.3 analyzed weekly variations in the absolute and relative arbitrage value of pure storage and CAES. In this section we explore what further insight can be gained by looking at the actual hourly operation, revenues, and costs for some representative weeks.

For a given hour of discharge, we can define the operating profits of a pure storage and CAES device in terms of the on- and off-peak price of energy (p^N and p^F, respectively), the efficiency of the pure storage device (η), the energy ratio and heat rate of the CAES device (ER and HR, respectively), the natural gas price (p^{NG}), and the VOM cost (v). The operating profit of a pure storage device is given by:

$$\Pi_s = p_s^N - \frac{p_s^F}{\eta} - v_s, \tag{1}$$

while the profit of the CAES device for a given hour is given by:

$$\Pi_C = p_C^N - p_C^F \cdot ER - HR \cdot p^{NG} - v_C. \tag{2}$$

The subscripts S and C on the on- and off-peak electricity price are meant to explicitly highlight the fact that due to differences in pure storage and CAES, the two devices may not charge and discharge during the same set of hours.

Note that in equation 1, the off-peak price is divided by the efficiency of the pure storage device, which is less than one. This reflects the fact that if the device has equal input and output power capacity, one hour of discharge will require purchasing energy over more than one hour. Conversely, in equation 2 the off-peak price is multiplied by the energy ratio, which is less than one and reflects the fact that for any given period of discharge, a CAES device will need to charge for less than one hour (and fewer hours than the pure storage device). This effect, combined with the use of natural gas can be observed in the hour to hour operation of the different devices, and their relative value.

During periods of high on-peak electricity prices, such as summers, the operation of storage and CAES devices can be quite similar. Figure 5 provides an example of optimized hourly operation of eight-hour pure storage and CAES devices during one week in the summer of 2007, when there is a large difference between on- and off-peak electricity prices. During this period of high utilization the hourly dispatch of the devices is nearly identical, with both devices completely charging and discharging once each day. The CAES device shows shorter charging times as expected since it can discharge for 1.42 hours at full capacity for each hour of charging. Because the discharge operation is similar the gross revenue (before accounting for charging energy or fuel costs) of both devices is nearly equal, (the pure storage device sells 56 kWh of energy per kW of capacity, while the CAES device sells 57 kWh) for a gross revenue of \$6.14/kW-week and \$6.26/kW-week, respectively. The difference in profitability of CAES versus pure storage is the tradeoff between fewer hours of charging and paying natural gas costs. The CAES device purchases 44% less energy, and the energy it purchases costs on average 18% less per kWh than the pure storage device, resulting in a 54% lower overall cost for purchased energy. This is the primary operational benefit of CAES over pure storage when both devices are operating at or near full capacity—not only does CAES require less purchased energy than pure storage, it can also typically choose from lower-cost hours, and will have a lower per-MWh cost of purchased energy. The total energy purchases for pure storage and CAES are \$2.69/kW-week and \$1.23/kW-week, respectively, while the CAES device purchases a total of \$1.49/kW-week worth of natural gas (at an average price of \$6.20/MMBtu). Overall, the net profitability is very close, at \$3.45/kW-week and \$3.53/kW-week for PHS and CAES, respectively.

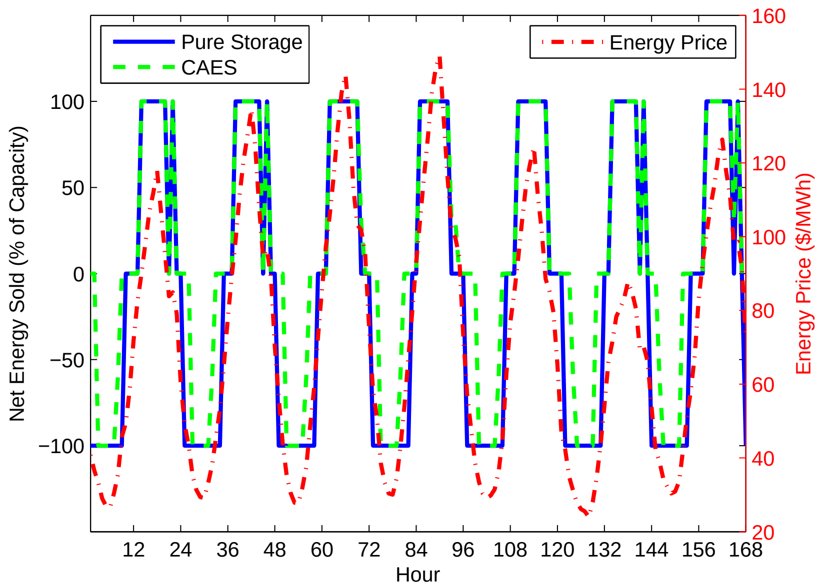

Figure 5: Dispatch of pure storage and CAES and energy prices over a one-week period in the summer of 2007.

In this summer week, the tradeoff between gas purchase and reduced electricity purchases are roughly equal, resulting in similar value for CAES and pure storage. In other times, when the on- and off-peak electricity price difference is lower, the cost terms in equations 1 and 2 tend to dominate, leading to very different operational characteristics and net revenue for CAES and pure storage. Figure 6 illustrates a period in winter during which the value of both pure storage and CAES is lower due to reduced demand and corresponding lower on-peak electricity prices. The daily operation and price profiles are also different, with two peaks and two shorter discharge periods in each day compared to the one longer discharge period in the summer. The price of natural gas in this case is also slightly higher (\$7.1/MMBtu) than in the summer example, resulting in a dispatch cost of about \$30/MWh for the CAES device.

In the example in figure 6, the electricity price difference is too small in the first day and in several of the morning peak periods for CAES to meet its dispatch cost requirements, while the pure device is still able to arbitrage this relatively small difference. Overall, during this week the CAES device sells 34% less energy than pure storage and receives 49% less revenue net of purchased energy and natural gas costs. Compared to the summer week, the net revenue of pure storage and CAES drops by 72% and 86%, respectively.

These examples illustrate that the primary disadvantage of CAES in its relative arbitrage value is the

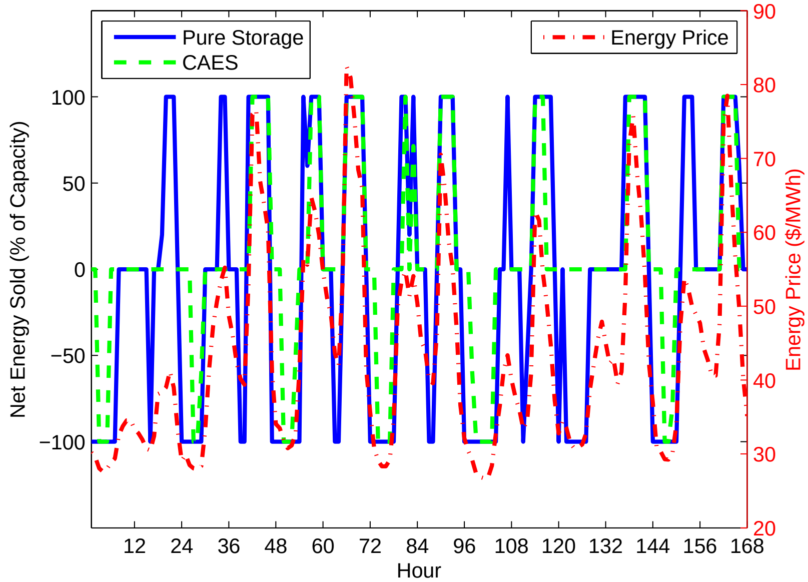

Figure 6: Dispatch of pure storage and CAES and energy prices over a one-week period at the end of 2007.

dispatch cost resulting from its use of natural gas, which limits CAES's ability to arbitrage low off-peak prices. This is shown in figure 7, which summarizes the minimum electricity price at which CAES and pure storage can profitably discharge energy, as a function of the price paid for charging energy. For pure storage, the lack of a fuel-related dispatch cost provides the ability to arbitrage small prices differences, providing a comparative advantage relative to CAES in such circumstances. As an example, pure storage could theoretically arbitrage the relatively small difference between periods where coal plants are at the margin, which typically bid in the range of $10-20/MWh. If the off-peak electricity price is $10/MWh, an 80%-efficient device could make money when the on-peak price exceeds $12.5/MWh plus VOM, which is relatively small for a pure storage device. Alternatively, a CAES device must always pay a variable dispatch cost—assuming a gas cost of $5/MMBtu and a heat rate of 4200 Btu/kWh, this dispatch cost alone is $21/MWh. Thus, in the same case of an off-peak electricity price of $10/MWh, the on-peak price must exceed $28/MWh, plus additional VOM costs. This issue could potentially have consequences for a system with a large amount of wind energy or other renewables with near-zero variable costs. If wind drives the prices to or near zero, a spread between this value and historical coal bids (excluding carbon costs) could be arbitraged by a pure storage device, but not by CAES unless the natural gas price were below $3-4/MMBtu.

Another consequence of the natural gas cost incurred by CAES is that its operation is much more erratic than that of pure storage during the winter, when on-peak electricity prices tend to fall much more than natural gas prices (this relationship is due largely to reduced electricity demand combined with increased natural gas use for heating). Figure 8 summarizes these operational differences between summer 2005 and the end of 2008 by showing the net energy discharged per kW of capacity for eight-hour pure storage and CAES devices over week-long periods. The figure shows that while there is some variability in the use of the pure storage device, it operates within a relatively narrow band in which it almost always discharges between 40 and 60 kWh/kW during each week. Figure 8 also highlights seasonal differences with pure storage and CAES being close to fully utilized during summer with most of the volatility occurring during other periods. During the four summer periods the pure storage device typically discharges 56 kWh/kW—corresponding to the device being fully discharged each day—and averages 52 kWh/kW overall for the year. Moreover, we see that the discharge of the pure storage device occasionally spikes up to 60 kWh/kW in winter. This is because the winter price and load profile tends to have a double peak during the day (due to morning and evening lighting and heating loads) rather than the single peak typically seen in the summer (due to midday cooling loads). This winter price profile allows for greater weekly discharge because of the possibility of

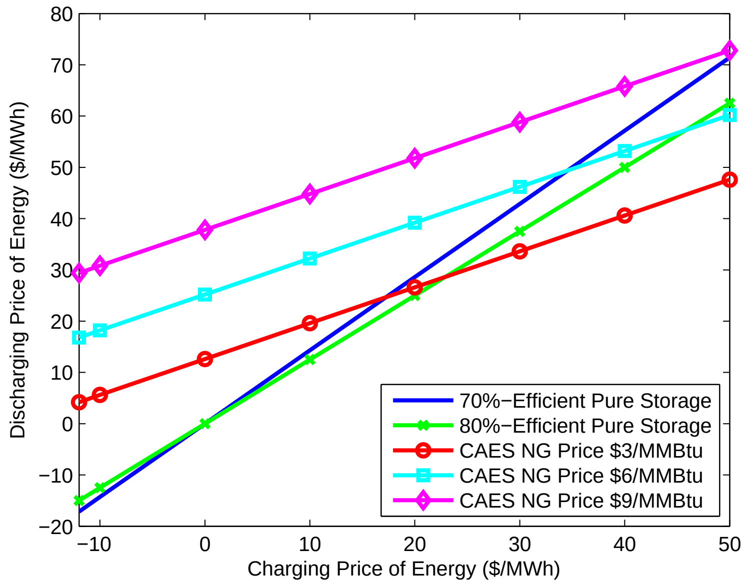

Figure 7: Minimum selling price of electricity with which pure storage and CAES would breakeven.

intraday arbitrage between the two daily peaks. This midday recharging and evening discharging behavior is also shown in figure 6. The CAES device, on the other hand, operates much more erratically and with a lower average utilization of approximately 48 kWh/kW and over a wider band, discharging between about 15 and 64 kWh/kW. Moreover, the operation of the CAES device varies much more from one weekly period to the next, compared to the operation of the pure storage device. This variability is borne out in the fact that the autocorrelation between the net sales of the CAES device between hour t and t+168 is 0.82 over the sample period in figure 8, whereas it is 0.87 for pure storage. This difference in the autocorrelation shows that operation of the CAES device is more variable from one week to the next as compared to pure storage, due to the effect that natural gas costs have on CAES operations.

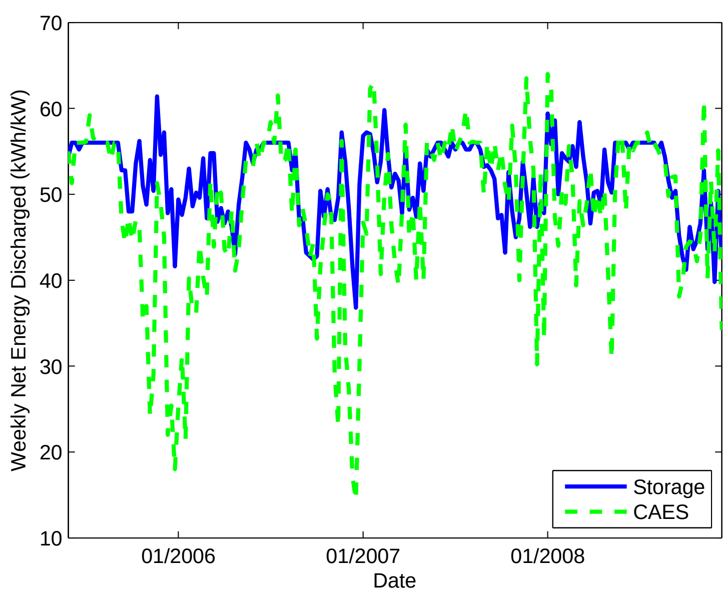

Figure 8: Net energy discharged per kW for an eight-hour pure storage and CAES device during weekly periods.

3. Net Revenue Distributions for Pure Storage and CAES and Forecasting Considerations

Figures 2, 3, 6, and 8 reveal the limitation of CAES in its ability to arbitrage small prices differences, especially with high natural gas prices. However figure 6 also suggests that the hourly operation of CAES in such times is likely to be more erratic than that of pure storage, which has some implications on the ability to forecast future operations absent perfect foresight of prices. Figure 9 shows this in more detail by comparing the week-to-week operation of a pure storage and CAES device over a two-week period. Specifically, the figure shows the difference in hourly net energy sales between week one and week two, as a percentage of the power capacity of the storage device. For example, in hour 141 of week one the pure storage device discharges at its maximum power capacity whereas in hour 141 of week two it charges at its maximum capacity—giving a difference of -200% of its rated power capacity.

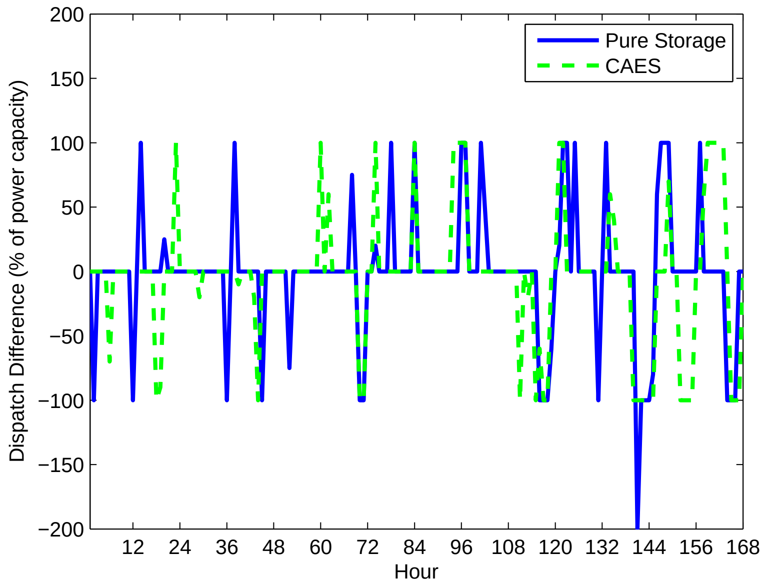

Figure 9: Difference in hourly net energy sales of pure storage and CAES between two consecutive weeks, as a percentage of power capacity.

Over this two-week period, the dispatch of the pure storage device is more consistent from one week to another. The operation of the pure storage device is identical in 127 hours between the two weeks as opposed to only 120 for the CAES device. Moreover, the sum of the absolute values of the deviations shown in figure 9 are only 38 for pure storage as opposed to 42 for CAES, showing that when partial charges and discharges are weighted accordingly, the operation of the pure storage device is more consistent between weeks.

These differences between successive weeks in hourly operational behavior have important implications for the actual value that could be captured by a storage device without perfect foresight of prices. The analysis so far has assumed perfect foresight of future hourly electricity prices. While this perfectly optimized value of storage is useful for providing an upper limit on the theoretical value of storage, in practice storage operators estimate the operation of storage devices without full knowledge of future prices.

Sioshansi et al. (2009) considered the use of a backcasting technique for an 80%-efficient pure storage device, whereby historical hourly price data from one week is used to determine future operation of the device in the following week. They showed that this simple technique can capture 85% or more of the potential arbitrage value that could be earned with perfect foresight of prices. The reason that this backcasting technique works so well for pure storage is because electricity prices tend to follow fairly predictable patterns, with high prices during the middle of the day and lower prices overnight. Because the previous days have a similar pattern to the following days, the backcasting technique tends to get operational decisions correct.

Moreover, because prices from the recent past are used, any longer-term seasonal differences in prices (for instance, if peaks occur in the morning and evening due to heating and lighting during the winter) are captured using the backcasting technique. In the case of CAES, however, the greater variability of operations suggests a lower value capture using this approach.

Figure 10 summarizes the net annual profits earned by eight- and 20-hour pure storage and CAES devices using the backcasting technique for a one-week optimization horizon during the seven years in our data sample.[8] The profits are given as a percentage of the profits that are theoretically attainable with perfect foresight of prices using the same optimization horizon. Because of the additional day used in our optimization model, the one-week optimization horizon is used to determine operational decisions for a six-day planning horizon (which is different from the optimization horizon used in section 2, in which operational decisions were made seven days at a time using an eight-day optimization horizon). The reason we assume that operational decisions are made six days at a time is because electricity prices tend to be lower on weekends than weekdays, which would result in more charging over weekends. Using an eight-day optimization horizon based on historical price data would not capture these persistent differences in prices between weekends and weekdays, since the price data would not follow the seven-day period of the week.[9] Figure 10 shows that while the backcasting technique works relatively well for the eight-hour pure storage device, capturing at least 89% of the theoretical perfect-foresight value of storage, it works relatively poorly for the eight-hour CAES device—5% to 10% worse than pure storage in the cases examined here. The difference in performance of the backcasting technique is directly tied to the variability in CAES operations, especially with lower on-peak electricity prices or high natural gas prices when the charge and discharge pattern of one week becomes a poor indicator of the following week. Lund et al. (2009) use a similar backcasting technique, based on daily as opposed to weekly historical data, in the Danish power market. They found that with CAES the backcast performs about as well as we show it to for pure storage in PJM—which is contrary to our finding that the backcast performs worse with CAES than pure storage. This difference in findings reflects the fact that the value and operational success of storage will depend on the specific price profiles and persistence of price differences of the system studied (which will depend on generation mix, load, and other factors), and that these profiles will generally differ between power systems, such as Denmark (which is part of the Nordic Power Exchange) and PJM.[10]

Figure 10 also shows the profits earned from backcasting with 20-hour storage devices, showing that the technique performs worse than with an eight-hour device for both pure storage and CAES. This is due to the fact that the incremental value between an eight- and 20-hour storage device is its ability to arbitrage between a greater number of hours, which will have a smaller spread in selling and buying price. As such, this incremental value will be much more sensitive to making correct operational decisions, due to the smaller margin from arbitraging these price differences. Indeed, using the backcasting technique with a four-hour pure storage device yields profits of at least 91% of profits that are attainable with perfect foresight, and in some cases as high as 95% of perfect-foresight profits. On the other hand, because a 20-hour storage device is less constrained in its operations, the total absolute profits earned (even with use of the backcasting technique) will be greater than that of a four- or eight-hour device.

Figures 11 and 12 summarize these differences in the performance of the backcasting technique by showing a histogram of the weekly perfect-foresight profits of pure storage and CAES, respectively, and the percentage of the perfect-foresight profits earned with backcasting.[11] The figures highlight some important

[8] In the case of the CAES device, we use both historical electricity and natural gas prices in the optimization.

[9] We compared the profits earned with the backcast using different planning periods of between one and 14 days, and found that the six-day planning period with a seven-day optimization horizon earned the greatest profits.

[10] It is difficult to directly compare PJM to the Danish power system given the large differences in generation mix and load patterns. The Danish power system peaks during the winter, while PJM peaks during summer afternoons. The Danish system relies much more heavily on wind (which also has different patterns from those in the U.S.), combined heat and power (CHP) plants, and hydroelectricity, while PJM had virtually no wind or CHP in the years analyzed and has very little hydroelectricity, relying largely on coal, gas, and nuclear generation. This combination of factors makes it difficult to make generalizations given the large number of variables driving the differences between on- and off-peak energy prices in the two systems.

[11] Both histograms have the same-sized bins with a width of approximately 0.44. The bin widths were determined in order to have 15 bins spread across the distribution of weekly profits for the pure storage and CAES devices.

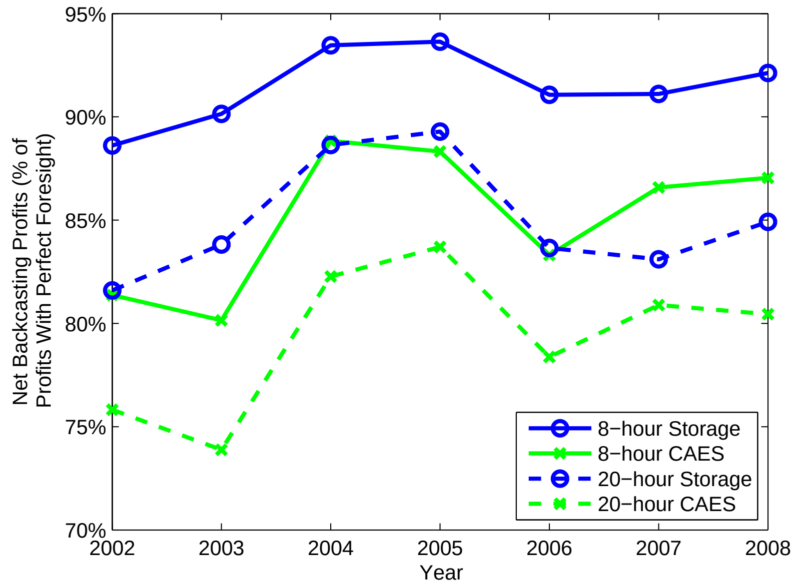

Figure 10: Net profits earned by eight- and 20-hour pure storage and CAES devices using backcasting technique and a week-long optimization horizon. Profits are given as a percentage of profits earned with perfect foresight of energy prices.

differences in both the distribution of perfect-foresight profits and the success of the backcasting technique for pure storage and CAES. The shape of the weekly perfect-foresight profit distributions are very different for pure storage and CAES due to the operational reasons identified and discussed in section 2 and also suggested by figures 8 and 9. Whereas the pure storage device earns an average weekly profit of about \$1.51/kW-week with perfect foresight, the CAES device is lower averaging only \$1.02/kW-week. The pure storage device also has a higher mode of about \$1.15/kW-week as opposed to only \$0.71/kW-week for CAES. This difference stems from the natural gas cost that the CAES device incurs. Specifically, on days with low on- and off-peak price differences the revenues of the CAES device net of natural gas costs are very small, leading to the more asymmetric distribution for CAES. In fact the weekly profits of CAES is less than \$1/kW 61% of the time, as opposed to only 26% of the time for pure storage.

When profits are high the backcasting technique works well for both CAES and pure storage—typically capturing over 90% of the profits with perfect foresight. This reflects the fact that these weeks have very large differences and predictable differences between on- and off-peak electricity prices, and minor errors in forecasting operational decisions are negated by the large differences in prices. The technique performs worse, however, during weeks with smaller profits available. This is due to the fact that these weeks will not have large on- and off-peak electricity price differences, making the determination of correct operational decisions much more important. In these weeks both profits earned and operational decisions made correctly tend to be lower. However, because these weeks have lower profits available, the poor performance of the backcast is compensated by its comparatively better performance during high-value weeks.

Any practical use of storage for arbitrage purposes will have to rely on forecasting, and our backcasting technique can likely be significantly improved by using load and weather forecasts to anticipate high- and low-price periods. The preceding analysis is useful, however, in showing that the value of CAES will tend to be much more sensitive than an 80%-efficient pure storage device to making operational decisions. As a result, CAES can be expected to generally perform worse than pure storage regardless of the forecasting technique considered.[12] Thus, not only is CAES generally less valuable than pure storage (with perfect foresight of prices), but it can be more difficult to capture CAES's intrinsic value in practice without perfect knowledge of future prices.

[12]This difference is partly due to our choice of an 80%-efficient pure storage device. For a 70%-efficient storage device the average annual value capture is similar to CAES.

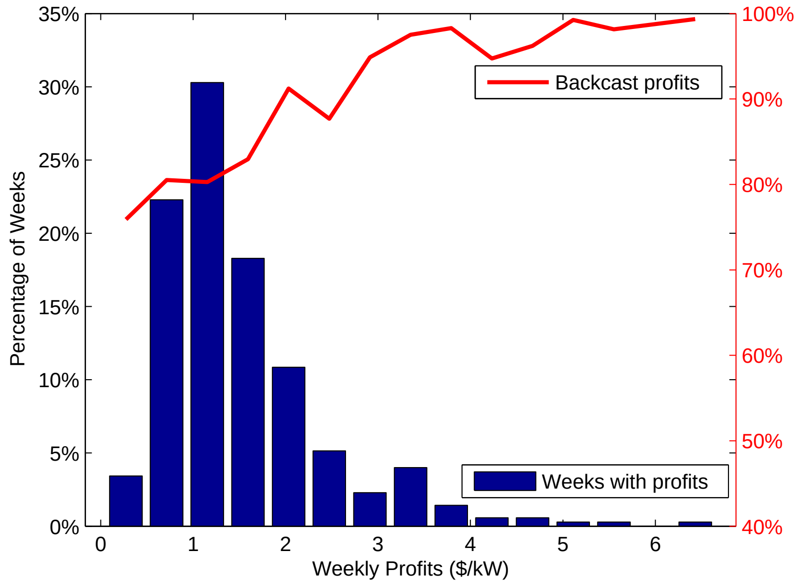

Figure 11: Histogram of weekly perfect-foresight profits of an eight-hour pure storage device with a one-week optimization horizon between years 2002 and 2008, and profits earned using backcasting technique. Profits given as a percentage of those attained with perfect foresight.

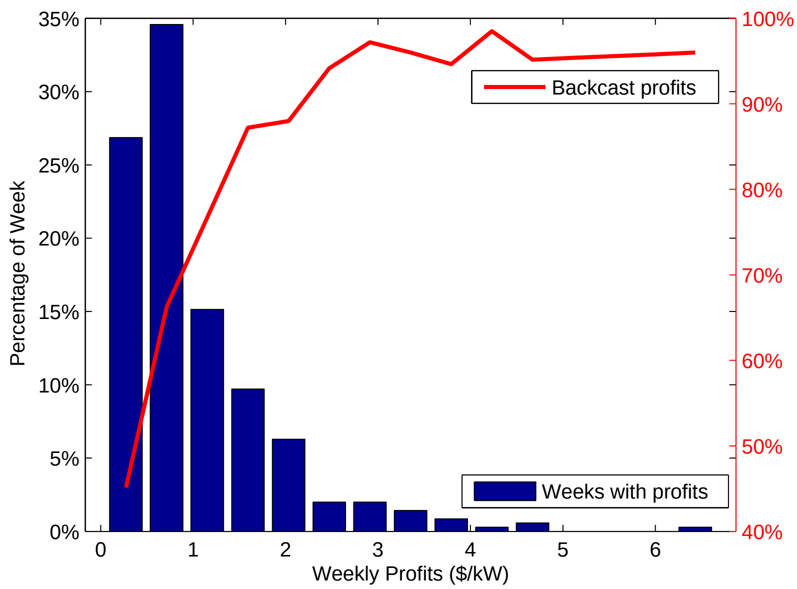

Figure 12: Histogram of weekly perfect-foresight profits of an eight-hour CAES device with a one-week optimization horizon between years 2002 and 2008, and profits earned using backcasting technique. Profits given as a percentage of those attained with perfect foresight.

4. Absolute and Relative Value of Pure Storage and CAES

4.1. Estimated Return on Capital for New Build, Expansions and Retrofits

The analysis so far indicates that the arbitrage value of CAES is less than that of an 80%-efficient pure storage device in the historical market evaluated. These differences depend greatly on a number of factors, such as natural gas prices, as discussed in section 2. The overall return on an investment in storage will depend on both the discounted net revenue as well as the cost of the investment—with new CAES builds expected to have a significant cost advantage over pure storage.

It has been some time since either a PHS[13] or a CAES plant has been built in the U.S., and there are a wide range of estimates for the cost of a new PHS or CAES facility. Moreover, these estimates are site-specific since both PHS and CAES require specific geological conditions. In addition the incremental costs of power and energy capacity for PHS and CAES are quite different; while both technologies are expected to have much lower incremental costs for energy capacity than electrochemical storage, the marginal cost of energy capacity is generally estimated to be much lower for CAES than PHS. For our analysis we compare similarly-sized storage devices (eight- and 20-hour) and do not carry out any detailed analysis of differences due to trade-offs in hourly marginal revenue and marginal cost.[14] Despite these caveats, some estimates of costs do exist (see, for instance, Deane et al. (2010) for recent estimates), and combined with the values estimated in sections 2 and 3, some insight can be gained into the absolute and relative profitability of PHS and CAES.

Recent estimates of CAES capital costs (in 2008 dollars) are in the range of \$750-1000/kW, while estimates of PHS are in the range of \$1500-2000/kW. Moreover, there are some possibilities for rebuilds or expansions of existing PHS plants, costing about \$1100/kW or less. The annual net arbitrage value (in 2008 dollars[15]) of a 20-hour 80%-efficient pure storage device ranges from \$72 to 127/kW-year over the seven-year period we examined. This arbitrage value averages \$93/kW-year and has a standard deviation \$20/kW-year. In contrast, annual net revenues for a 20-hour CAES device is lower and ranges between \$48 and 81/kW-year, with an average of \$67/kW-year, and a smaller standard deviation of \$14/kW-year. Because of the differences in the impact of natural gas prices on the value of pure storage and CAES, these high and low arbitrage values for pure storage and CAES are not coincident.

Because the arbitrage value of pure storage and CAES will generally fluctuate, we bound the potential range of the annualized return on investment by using the average value over the seven-year period and also showing the values corresponding to plus and minus one standard deviation. For PHS this leads to a annual arbitrage values of \$73 to 113/kW-year, and \$53 to 80/kW-year for CAES. Table 2 summarizes the annualized return on investment for new PHS and CAES builds with different capital costs, and shows that these arbitrage values correspond to quite low returns on investment in the range of 4 to 8% and 5 to 10% respectively (using real interest rates).[16] This is a slight oversimplification since the distribution of the arbitrage value is not normal.

This calculation neglects some additional revenues that storage devices might earn. For instance, in an energy and capacity market, such as PJM, storage may also be eligible for capacity payments. Some of the difficulties in successful capacity market design and implementation have led to extremely wide variation in the size of capacity payments. A range of capacity payments consistent with both historical payments and recent auctions, is \$20 to 60/kW-year.[17] Adding this potential revenue source, and assuming a mid-point value of \$40/kW-year, increases the return on investment significantly for PHS to 5 to 10% and for CAES to 9 to 16%, as shown in table 2. While CAES appears more attractive than PHS under our assumptions, it will depend on what the actual site-specific capital costs are for the two technologies, as well as location.[18] Moreover, enhancements to existing pumped storage facilities may offer a relatively attractive option. Deane et al. (2010) estimate that existing PHS plants can be expanded or rebuilt in some cases for as little as \$1100/kW or less, which would yield a return on investment in the range of 9 to 14%, as shown in table 2.

[13]Because of the currently high cost of battery energy storage, we focus on PHS as the pure storage technology to which we compare CAES.

[14]The actual marginal costs of the energy component of PHS and CAES are very site-specific and a function of size.

[15]All annual values are adjusted to 2008 dollars using historical Consumer Price Index data.

[16]The real interest rate has the impact of annual inflation netted out, which was about 2.5% over the last 10 years e.g. an 10% real discount rate would correspond to a 12.5% nominal discount rate.

[17]The \$60/kW value comes from an estimate by Felder and Newell (2007) of the cost of new entry for combustion turbines of \$58/kW-year

[18]We have used average marginal hourly electricity prices in our analysis. As shown in Sioshansi et al. (2009), some locations might have an arbitrage value variation of plus or minus \$20/kW-year or more, depending on local congestion prices.

Table 2: Annualized return for PHS and CAES under various capital cost and revenue scenarios (%).

PHS

Capital Cost	Revenue Scenario: Arbitrage Only			Arbitrage and Capacity		
(2008 $)	$73/kW-yr	$93/kW-yr	$113/kW-yr	$103/kW-yr	$133/kW-yr	$153/kW-yr
$2000/kW	3.7%	4.7%	5.7%	5.2%	6.7%	7.7%
$1500/kW	4.9%	6.2%	7.5%	6.9%	8.9%	10.2%
$1100/kW	6.6%	8.5%	10.3%	9.4%	12.1%	13.9%

CAES

Capital Cost	Revenue Scenario: Arbitrage Only			Arbitrage and Capacity		
(2008 $)	$53/kW-yr	$67/kW-yr	$80/kW-yr	$93/kW-yr	$107/kW-yr	$120/kW-yr
$1000/kW	5.3%	6.7%	8.0%	9.3%	10.7%	12.0%
$750/kW	7.1%	8.9%	10.7%	12.4%	14.3%	16.0%

When actual value capture associated with the lack of perfect foresight is taken into consideration the prospects of pure storage relative to CAES improve. Assuming that CAES captures 80% of the potential value with perfect foresight of prices, as opposed to 90% for PHS reduces the 12.1% return on investment for a PHS rebuild or expansion to 10.9%, while the 14.3% return on investment for CAES is reduced to 11.4%—the difference in this case has been reduced from 2.2% to 0.5%. This comparison carries the obvious caveat, which we mentioned in section 3, that better use of forecasting will likely help reduce the arbitrage losses for both PHS and CAES. However, given the greater sensitivity of the revenues from CAES operations to on- and off-peak price differences, it is likely that better forecasting would not eliminate the difference in the performance of CAES without perfect foresight of prices.

4.2. Impact of Market Structure and Ownership Considerations on Breakeven Cost of Storage

So far we have considered the likely annualized rate of return for pure storage and CAES. It is useful to view the value of storage from a different perspective, and pose the question 'what is the breakeven capital cost for pure storage and CAES?' In this context, the choice of discount rate is important because it sets the maximum supportable 'economic' capital investment—that is to say capital costs need to be lowered to this value for storage to be economic given certain assumptions about annual net revenue. For example, assuming a 12% discount rate, a 40-year life for both PHS and CAES, and a net annual revenue of $140/kW-year for PHS would support a capital investment of up to $1220/kW.[19] This is not enough, therefore, to support a $1500 to 2000/kW PHS device, though it is sufficient to support some estimates of the cost of rebuilding or expanding existing PHS facilities. It is worth noting that in a deregulated market for a private-sector investor this is a relatively low expected rate of return, and the required rate of return could be significantly higher (though this depends on the expected uncertainty of the future net cash flows); a 15% discount rate would, for example, require the capital cost target to be lowered to under $1000/kW.

Jenkin and Weiss (2005); Sioshansi et al. (2009) pointed out that in a restructured market, such as PJM, a private sector investor may not have the proper incentives to build the optimal amount of storage, and that it might be better to treat storage as a regulated asset, similar to transmission or distribution infrastructures. While not discussed explicitly in these papers, such a decision will also have a significant impact by increasing breakeven cost for storage to be economic, even if we neglect potential additional revenue streams from other sources such as congestion relief, benefits of deferred transmission, and better grid and asset utilization. For

[19]This approach estimates returns and breakeven costs based on simple cash flow (earnings before interest, taxes and depreciation), with interest rate and depreciation potentially providing offsetting effects with taxes. Alternative financing assumptions could have a significant impact on overall returns, though this would be highly dependent on assumptions made, including the possibility of investment tax credits.

a specific investment switching to the lower discount rate will increase the breakeven cost, and could in some cases make an otherwise-marginal investment attractive. This may increase social welfare, especially if the effect of harder to quantify benefits, such as transmission deferral and better system utilization, are included. For example, if storage were treated as a regulated asset and the discount rate set to a lower rate of 8% (which would correspond to 10.5%, if adjusted for historical inflation) then the breakeven cost of storage increases to $1730/kW—an increase of over 40% above the previous breakeven cost estimate—which is in the cost range for PHS. Regulatory structure and rules for storage in wholesale electricity markets can therefore have significant impacts on whether or not storage is viable, above and beyond the net revenue considerations discussed in Sioshansi et al. (2009). Whether the switching to a lower utility-wide discount rate will generally increase social welfare is less clear since under regulation some investment risks are passed onto ratepayers, for which they are not traditionally compensated.[20]

Our earlier analysis suggested that with a 12% discount rate CAES was potentially more attractive than PHS because the lower likely capital cost more than offset the reduced net revenue. With this 12% discount rate, a CAES device earning net revenues of $110/kW-year supports a maximum capital investment of $960/kW. While this is less than the $1220/kW calculated for PHS, it is clear that if the estimated capital costs for CAES is in the $750 to 1000/kW range, CAES is relatively more attractive than PHS. On the other hand if CAES is treated as a regulated asset, with an 8% discount rate, the breakeven cost increases to $1360/kW. Thus treating PHS and CAES as regulated assets increases the breakeven cost of these storage technologies by about $500 and 400/kW, respectively. These increases can make specific PHS and CAES investments more attractive, depending on net revenue assumptions. Figure 13 shows the impact of different discount rate and net cash flow assumptions on the breakeven costs of CAES and PHS.

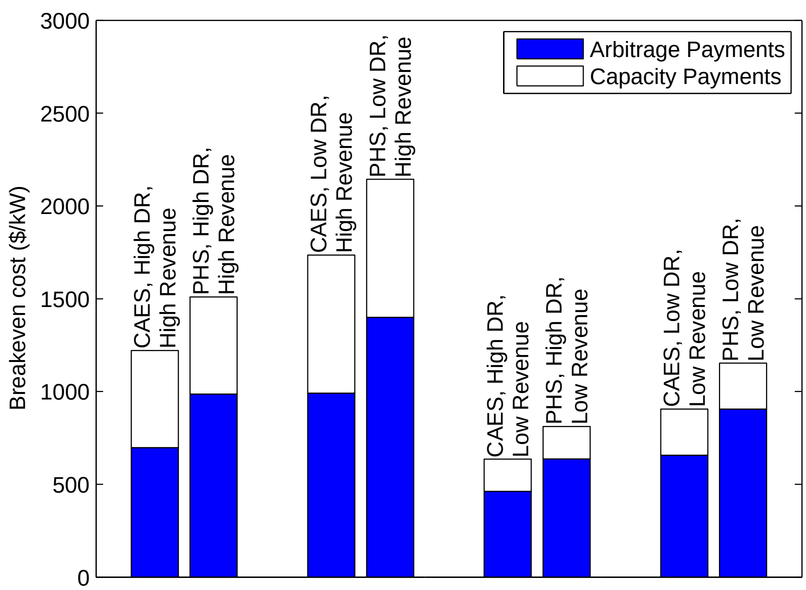

Figure 13: Comparison of breakeven cost of PHS and CAES under different net revenue and discount rate (DR) assumptions. High revenues correspond to arbitrage profits of $80 and 113/kW-year for CAES and PHS, respectively, and capacity revenues of $60/kW-year. Low revenues correspond to arbitrage profits of $53 and 73/kW-year for CAES and PHS, respectively, and capacity revenues of $20/kW-year. High and low discount rates are 12 and 8%, respectively.

[20]This is because such a change does not necessarily make the operation of the asset less risky, but rather the discount rate reflects the premium needed for utility investors'exposure to their share of the asset risk under regulation. Cost-based regulation usually allocates some of the asset performance risk to ratepayers, so that under regulation the lower rate may be offset to some degree since ratepayers will subsidize investments that prove to be unattractive. The net welfare effect will most likely depend on specific circumstances, and the answer will also depend more generally on one's view of the relative merits and efficiency of power system investments in restructured and regulated markets. This topic is a subject of on-going debate and lies outside the scope of this paper.

An important question raised by this analysis is whether storage would be treated as a regulated asset, similar to transmission or distribution assets. Jenkin and Weiss (2005); Sioshansi et al. (2009) note that depending on its location, storage can have some transmission-related benefits, which could be used as an argument in favor of this treatment. If so, this raises a related question of whether PHS, other pure storage, and CAES would be treated 'equally' as regulated assets. For example, under one possible scenario PHS and pure storage may be treated as regulated assets, while CAES is disallowed this treatment as it is considered to be more akin to gas-fired generation (due to its hybrid nature). In such a case, PHS and pure storage could have, depending on assumptions, a roughly $300 to 500/kW increase in their breakeven costs relative to CAES, which could significantly alter the relative economic prospects of the two technologies. A slightly related issue is whether some of the value streams, such as capacity payments, might be treated differently for pure storage and CAES. For instance, because the CAES expander is essentially a gas combustion turbine, a system operator may view CAES as having more capacity value if the turbine could be operated without stored energy.[21]

5. Discussion and Conclusions

Wholesale electricity markets in many regions make it possible to evaluate the potential arbitrage value of energy storage in many parts of the country and around the world. There is significant interest in the use of CAES, PHS, and other pure storage technologies, and this interest is growing due to the impact of integrating large amounts of variable renewable energy. This paper examined the arbitrage value of pure storage and CAES in PJM under a simple price-taking assumption.

Our analysis shows that the net annual arbitrage value of an 80%-efficient pure storage device is generally significantly greater than that of CAES. This is largely due to the impact of the cost of natural gas during periods of the year in which on- and off-peak electricity price differences are low. We showed that in the summer months, the relatively high on- and off-peak electricity price differences and the reduced charging time needed by CAES makes the value of CAES comparable to (and in some cases greater than) that of pure storage. While increasing natural gas prices will decrease the value of CAES relative to pure storage, the value of CAES still increases in PJM with increased natural gas prices because the impact of higher natural gas costs is outweighed on average by increases in the on- and off-peak electricity price spreads.

These results can be seen by looking at the weekly net revenue distributions for CAES and pure storage. While both distributions are asymmetric and positively skewed, the CAES distribution has much more weight in the lower values of less than $1/kW-week. Related to this is the fact that optimal week-to-week operations of CAES is more variable than that of pure storage. The impact of this is that while value capture using our simple backcasting approach is typically 85% or higher for pure storage it is reduced by 5 to 10% for CAES.

While pure storage generates greater net revenue, the capital costs of CAES are generally anticipated to be much lower than pure storage (with PHS being the lowest-cost pure storage technology). As a result the returns on investment are actually quite similar in PJM over the years considered, depending on capital cost assumptions. When potential additional revenue from capacity payments of $20 to 60/kW-year are included the return on investment for new builds is 9 to 16% for CAES and 5 to 10% for PHS, depending on specific revenue and cost assumptions. PHS rebuilds or expansions, which have been estimated to cost $1100/kW or less, yield more attractive returns on investment compared to new builds of between 9 and 14%, suggesting such investments may be comparable or potentially more attractive than CAES. This advantage becomes especially apparent if we consider the fact that value capture without perfect foresight of electricity prices by CAES may be 5 to 10% lower than for pure storage

In practice large amounts of storage will reduce arbitrage because discharge will reduce prices and charging will increase prices. Sioshansi et al. (2009) estimated that for 1 GW of pure storage in PJM this

[21] The issue of whether or not storage can be regulated, and if so for what applications, is subject to a number of case studies by the Federal Energy Regulatory Commission and others. At this point the rules are evolving and the decisions of whether or not to try to fit storage within the existing market design framework, or make more substantive design changes to reflect storage's unique array of benefits remains to be seen.

could lead to a 10% reduction in value of arbitrage. Sioshansi et al. (2009) also discussed how ownership, market and contract structure can matter greatly when considering overall societal benefits, and in particular made the point that if storage was treated as a regulated asset in a market such as PJM the societal welfare gains would more than offset such arbitrage losses. In this paper we also showed there might be further potential benefits if storage could be treated as a regulated asset, since the breakeven cost of PHS and CAES could increase substantially, though the absolute value will vary widely depending on net revenue and discount rate assumptions. Such differences could potentially have a marked impact on storage investment decisions and hence the economics and viability of integrating large amounts of variable renewables, such as wind, which in turn could be of societal value given the inherent difficulties in separating out and valuing certain storage applications.

While the focus of this paper is on arbitrage associated with load shifting it is worth noting that storage has many sources of value beyond arbitrage, such as improved system utilization and deferred transmission and distribution investment. As discussed, the value of storage can also depend intimately on ownership, market, and contract structure considerations. A number of studies, such as that of Walawalkar et al. (2007), have concluded that arbitrage alone is not sufficient to justify building storage and point to other sources of value, such as transmission deferral. It is, however, worth pointing out that the value of storage is made up of component sources of value, and that in the case of transmission deferral or a number of other potential applications with societal benefits, the value of arbitrage due to load shifting and the use of low-cost energy in place of higher-cost energy is likely to be one of the largest components of value when used for multiple applications. In summary, any valuation framework for storage will need to include all components of which arbitrage-related value is often likely to be significant.

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