Title: The Value of Compressed Air Energy Storage in Energy and Reserve Markets

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Abstract
Storage devices can provide several grid services, however it is challenging to quantify the value of providing several services and to optimally allocate storage resources to maximize value. We develop a co-optimized Compressed Air Energy Storage (CAES) dispatch model to characterize the value of providing operating reserves in addition to energy arbitrage in several U.S. markets. We use the model to: (1) quantify the added value of providing operating reserves in addition to energy arbitrage; (2) evaluate the dynamic nature of optimally allocating storage resources into energy and reserve markets; and (3) quantify the sensitivity of CAES net revenues to several design and performance parameters. We find that conventional CAES systems could earn an additional \$23±10/kW-yr by providing operating reserves, and adiabatic CAES systems could earn an additional \$28±13/kW-yr. We find that arbitrage-only revenues are unlikely to support a CAES investment in most market locations, but the addition of reserve revenues could support a conventional CAES investment in several markets. Adiabatic CAES revenues are not likely to support an investment in most regions studied. Modifying CAES design and performance parameters primarily impacts arbitrage revenues, and optimizing CAES design will be nearly independent of dispatch strategy.

1. Introduction

Several factors have led to the increased interest in the use of electricity storage. These include the development of electricity markets for energy, capacity, and operating reserves [1], the potential use of storage to aid integration of variable renewable generation [2,3,4,5,6,7], and the potential for storage to defer the expansion of transmission and distribution assets.

Storage devices are frequently categorized by their performance characteristics, and the applications they serve. Short-term storage, on the order of minutes, can be used to provide operating reserves such as frequency regulation and contingency reserves. Longer-term storage, on the order of hours to days, can provide load-leveling and peak capacity services, in addition to potentially providing shorter-term grid services as well. Technologies currently deployed for these applications include pumped hydroelectric storage (PHS), compressed air energy storage (CAES), and certain battery technologies [7].

While storage devices can be used to provide a range of grid services, it is frequently challenging to quantify the value potentially captured by storage devices in each application, and to identify market mechanisms for monetizing these value streams [1]. The development of electricity markets over the past decade has clarified the value provided by some storage applications in regions with markets (for example providing energy arbitrage, regulation and reserves), but not all applications (for example, improving power quality and reliability, and reducing the need to expand transmission and distribution resources) [1].

This study focuses on quantifying the potential value of CAES devices in several U.S. markets by providing load shifting and reserves services. We use historical energy and operating reserve price data from several U.S. electricity markets to simulate CAES economic performance in a variety of locations, including several locations proposed for new CAES installations. CAES economics are quantified using a model that optimally dispatches a CAES device based on historical market prices, and subject to CAES performance criteria. We simulate two CAES dispatch methods: (1) dispatch to maximize net revenue from energy arbitrage (following previous methodology from [8]), and (2) co-optimized dispatch to maximize net revenue from both energy arbitrage and providing contingency reserves (spinning and non spinning reserves). We also use this model to explore the sensitivity of CAES economics to a range of design and performance parameters. This analysis also demonstrates how the optimal configuration of a CAES device (including the relative size of the charge and discharge components) might change as a function of device operation.

2. Modeling CAES economics

Several previous studies have estimated storage revenues of single applications, or multiple applications, using simplified dispatch assumptions and historical market data [1,9]. This study combines historical market data with an optimized dispatch approach to estimate the value of a co-optimized energy storage device, extending the arbitrage only analysis performed by Sioshansi et al. [10] and Sioshansi et al. [8]. Our focus is to examine how a co-optimized device would dynamically allocate storage resources to serve three different markets (energy, spinning, and non-spinning reserves) and to quantify the associated increase in storage net revenue.

2.1. Electricity Markets

As of 2010, wholesale energy markets were operating in about 30 states, serving more than two-thirds of the U.S. population [11]. Electricity market data provides a means for evaluating the historical economic performance of energy storage devices. We use historical hourly day-ahead energy and contingency reserves (spinning and non-spinning reserves) data from several markets and years listed in Table 1. We simulate CAES performance in each market at a reference location that corresponds with the location of a proposed CAES projects within that region. The reference region often corresponds to a fairly low-value region within each market. We also simulate a high value location representing the region with the largest difference between off- and on-peak prices within each market, and providing an approximate upper bound to CAES economic performance within each region. Additional data used to characterize locations within each market is included in table A.1 in the appendix.

During the 2002-2009 analysis period, there were several market trends that affect CAES economics. Electricity prices peaked in 2007-2008, and decreased significantly in 2009 with a corresponding decrease in the value for energy arbitrage and contingency reserves. Since the nodal day ahead CAISO market began operation in 2009, CAES performance in this year is not reflective of mean performance, rather it is a snapshot of CAES performance in a depressed electricity market.

We use the monthly mean natural gas prices for electric power producers from the U.S. Energy Information Administration (EIA) at the state level[1]. Natural gas prices also peaked during the 2007-2008 period [12], which typically increases the value of bulk energy storage [8], and decreased in 2009.

2.2. CAES operational parameters

CAES devices store electrical energy by using an electric motor to compress air, which is then stored in a reservoir (typically an underground formation). Compressed air is then used at a later time to generate electricity by expanding the compressed air through a series of turbines. Two general types of CAES systems have been deployed or are under consideration. The first is conventional or "diabatic" CAES, which burns natural gas in an expansion turbine similar to a combustion turbine plant [13]. The

[1] http://tonto.eia.doe.gov/dnav/ng/ng_pri_sum_dcu_nus_m.htm

performance of conventional CAES is characterized by the fact it uses two energy inputs: compressed air from stored electricity, and natural gas fuel. As a result, instead of a single round-trip efficiency, conventional CAES efficiency is characterized by the device's heat rate (amount of natural gas energy used to generate each kilowatt hour (kWh) of electricity, given in units of kJ/kWh) and energy ratio (amount of electrical energy input per unit of electrical energy output). Conventional CAES energy ratios are less than one, meaning more energy is generated than stored, because natural gas is used during generation.

There is interest in developing CAES systems that do not burn fossil fuels. A few approaches have been explored, which include adiabatic CAES [14,15] and isothermal CAES. Adiabatic CAES systems store the heat generated from compressing air and use it to re-heat expanding air during the generation cycle. While there are no existing adiabatic CAES systems, efficiencies have been estimated from thermodynamic calculations, and the range of estimates is provided in Table 2. Isothermal CAES systems compress and expand air near-isothermally (constant temperature), and do not use fuel during the expansion cycle[2]. Isothermal CAES is in the early stages of development and potential costs and performance have yet to be well documented. We use the performance of adiabatic CAES as a proxy for isothermal CAES.

Table 2 summarizes CAES performance parameters for conventional and adiabatic systems. These include performance parameter ranges from the literature, the parameters used to characterize reference CAES performance in section 3, and the ranges explored in the sensitivity analysis in section 4. Basic CAES design and performance parameters that are considered in this work include conventional CAES heat rates and energy ratios and adiabatic[3] CAES round trip efficiencies. Additional parameters considered include the relative size of CAES compressors (charging capacity in MW) and expanders (discharging capacity in MW), the minimum charging and discharging limits (defined as the minimum operating level, characterized as a fraction of peak charge or discharge capacity), and the amount of energy storage capacity (MWh) characterized by the number of hours of discharge at peak expander capacity.

2.3. Model

A mixed integer linear program model was developed to simulate the optimal dispatch of conventional and adiabatic CAES devices into historical day ahead energy and reserves markets. For each year, the linear program determines the optimal hourly CAES dispatch by maximizing net revenue based on hourly electricity and reserves prices, and the cost of natural gas and O&M[4], subject to the operational constraints of conventional and adiabatic CAES systems. The optimization was conducted in two weeks periods, allowing for intra- and inter-day arbitrage opportunities, while reflecting the fact that storage operators are not likely to make dispatch decisions far into the future. We assume perfect foresight of future electricity and reserves prices in the optimization, and we evaluate the impact of this assumption in section 4.5. The co-optimized dispatch model is based on an arbitrage only model described in detail in *Sioshansi et al.* [10], with modifications to include the additional operating modes shown in Figure 1.

[2] For example, www.sustainx.com and www.generalcompression.com.
[3] From here forward we use only the term adiabatic as a proxy for CAES types that do not require natural gas fuel
[4] Net revenue is defined as the gross revenue from electricity and reserves revenue minus operating costs which include electricity and natural gas costs, and operations and maintenance (O&M) costs.

Figure 1 illustrates the operating modes for a CAES device that is dispatched for energy arbitrage and to provide spinning and non-spinning reserves[5]. We assume that a CAES device must be operating (spinning) to provide spinning reserves, and that it can provide non-spinning reserves up to its maximum output capacity while it is idle or charging. While the storage device is charging, it can provide spinning reserves up to the amount that it is charging, and non-spinning reserves up to its generation capacity. During idle operation, it can bid non-spinning reserves up to its generation capacity. During partial discharge, the storage device will receive electricity revenues for the amount of electricity it generates, and can sell the difference between output and its maximum generation capacity as spinning reserves. During full discharge, the CAES device generates at full capacity to sell electrical energy, and there is no remaining generation capacity to provide additional reserves. A CAES device can also operate in a partial charge mode, and sell both spinning reserves up to the amount it is charging and non-spin reserves up to its maximum generation capacity.

In using historical market prices to characterize CAES economics, we implicitly assume that dispatching the storage device does not affect market prices. This so called "price-taker" analysis is likely to capture the value of the first small storage devices added to the system, but does not capture the feedback between storage dispatch on energy and reserves prices. It also does not capture any increase in storage value that may occur if there is significant deployment of variable renewable generation resources such as wind or solar.

Lastly, the reference CAES simulations assume perfect foresight of day-ahead energy and reserves prices. We explore the impact of imperfect foresight and non-optimal dispatch on CAES economics in section 4.4.

3. Results

We simulated CAES net revenues for 8 system types in each market and year, representing the combination of: (1) conventional and adiabatic CAES systems characterized by the values in Table 2; (2) reference and high-value locations (Table 1); (3) energy arbitrage and co-optimized (energy and contingency reserves).

3.1. CAES Dispatch Characteristics

Figure 2 shows a representative CAES dispatch for an arbitrage only and co-optimized CAES system from the reference location in the NYISO market from July 5-7, 2007. Day-ahead energy, spinning reserve and non-spinning reserve market prices are also shown. As shown by *Sioshansi et al.* [10] a storage device dispatched for energy arbitrage will charge and discharge at full capacity during the hours when arbitrage is profitable, and will spend a large fraction of time idle during the hours when arbitrage is not profitable. In figure 2, the arbitrage only CAES device predictably charges at maximum capacity when electricity prices are lowest from midnight through early morning (e.g. hours 0-7), and discharges at maximum capacity when prices are high during midday and evening in July (e.g. hours 10-19). The co-optimized CAES device shows similar charging characteristics, but spends a large fraction of time discharging at partial capacity and selling both energy and reserves. The difference between dispatch characteristics can be relatively small (July 6th) or fairly significant (July 5th and 7th), making it difficult to

[5] Spinning and non-spinning reserves are rarely called [15], and co-optimizing for these markets primarily impacts storage revenues by enabling storage devices to sell capacity in these markets.

capture the full value of a co-optimized device with a fixed or simple allocation of storage resources into energy and reserve markets. These trends are seen in all seasons, device locations, and for adiabatic and conventional CAES systems.

Figure 3 shows conventional CAES dispatch statistics for three years of operation in NYISO for both the reference and high-value region. CAES dispatch characteristics are relatively similar for each device type in a given location. Arbitrage only CAES devices spend less than 50% of the time charging or discharging in the reference region, and over 70% of the time charging or discharging in the high value region. These devices charge for less time than they discharge, because the use of natural gas means they generate more energy than they store. In the reference region, the arbitrage only device charges and discharges for far less time in 2008 and 2009 than in 2007 because of the relative price of natural gas to wholesale electricity. Co-optimized CAES systems spend far more time discharging than arbitrage only devices, and the majority of discharge is at partial capacity while providing both energy and spinning reserves. CAES devices spend up to 50% of the time partially discharging in the reference region, and up to 40% of the time partially discharging in the high value region. Both CAES dispatch methods spend far less time idle in the high value region, where the spread in off- and on-peak electricity prices is high enough to make arbitrage profitable for more hours during the year. Dispatch statistics are calculated for CAES devices with equally sized compressors and expanders.

Table 3 shows corresponding NYISO market characteristics and CAES net revenues for these years and locations. Net revenues are shown here, and elsewhere, in units of 2009 U.S. dollars per kilowatt of expander capacity per year, which we write as $/kW-yr. Detailed results for all regions are provided in the Appendix. While CAES operating characteristics are primarily driven by device location and dispatch strategy, CAES net revenues are also strongly driven by interannual variations in electricity and natural gas prices. Table 3 shows that interannual price variability and device location can change historical CAES revenues by a factor of two to three. The additional revenue from co-optimizing for reserves is not as highly dependent on device location or year, and generates $21-26/kW-yr of additional revenue for 5 of the 6 cases.

The dispatch statistics shown in Figure 3 suggest a fairly fixed allocation of storage resources to energy arbitrage and reserves, particularly for the high value region. However, the optimal allocation of resources varies seasonally, regionally, and based on device characteristics, as shown in Figure 4. This figure shows CAES discharge characteristics for co-optimized conventional and adiabatic CAES systems simulated in the NYISO reference location. Discharge characteristics are represented by the fraction of time a CAES device spends partly or fully discharging over sequential two week periods in each year for the average of 2002-2009 and for two representative years (2003 and 2008).

CAES discharge frequencies show some seasonal trends, and strong interannual variations from those trends. For example, CAES systems discharge at full capacity more frequently during the summer, when difference between off- and on-peak electricity prices are highest, than in other seasons. There is a corresponding decrease in the frequency of partial discharge during the summer. However, CAES dispatch characteristics for 2003 and 2008 show strong deviations from each other, and from the 8 year mean dispatch. CAES discharge frequencies also show large shifts from one two-week period to the next. This makes it challenging to define a simple allocation of storage resources to energy arbitrage or reserves markets based on past CAES performance, or mean performance.

3.2. Net Revenue

Figure 5 provides both the revenue generated by an arbitrage only system (x-axis), and a co-optimized system (y-axis) for all device locations and years. There is a large range in arbitrage only CAES net revenues ($15 - 120/kW-yr) based on the electricity market, location within the market, and interannual variations in natural gas and electricity prices. The additional reserves revenue generated by co-optimized systems relative to arbitrage only systems is shown by the distance of each point on the scatter plot above the 1:1 line. For most CAES device types and locations the additional revenue generated by a co-optimized system is typically in the range of $10 – 30/kW-yr

There is a strong linear relationship between co-optimized and arbitrage only net revenues (R^2=0.89 - 0.95), The additional revenues generated by co-optimized conventional CAES devices are about $15/kW-yr plus about an additional 0.13 times arbitrage only net revenues (R^2=0.95). The additional revenues generated by co-optimized adiabatic CAES devices are about $16/kW-yr plus about an additional 0.22 times arbitrage only revenues (R^2=0.89). In aggregate, dispatching a CAES device to provide operational reserves in addition to energy arbitrage increases annual net revenues by $23 ± 10/kW-yr for conventional CAES devices and $28 ± 13/kW-yr for adiabatic CAES devices. Reserves revenues are frequently similar in the reference and high-value locations, primarily because most electricity markets have far fewer pricing regions for reserves than energy. It is common for devices located in the reference locations to earn higher reserve revenues, because the devices spend more time dispatched at partial capacity and selling reserves (Figure 4). PJM shows very low reserve revenues in the reference location in 2005 and 2006, and then similar reserve revenues to the high-value location from 2007-2009. This difference in revenue characteristics represents a change in the PJM market, where reserves were priced in separate markets before 2007, and priced in the same market in 2007 and beyond.

Co-optimized CAES devices frequently earn higher net revenues because they have lower operating costs associated with providing reserves in addition to earning higher gross revenues. An arbitrage only CAES device will dispatch for hundreds of hours every year to earn marginal, but positive, net revenues. During these hours of low net arbitrage revenues, a co-optimized CAES system will sell reserves and earn higher gross revenues, while discharging less energy which reduces the amount of electricity that needs to be purchased to recharge the storage reserve. This trend is true for both conventional and adiabatic CAES systems.

Figure 6 compares conventional CAES net revenues to those generated by adiabatic CAES systems. In general, these net revenues are similar. However, there is a trend showing that conventional CAES systems generate higher net revenues in high value locations, and adiabatic systems generate higher net revenues in the reference locations. This is driven by the relationship of the additional cost of burning natural gas in a conventional CAES system with the reduced need to purchase electricity[6]. In high value locations, the ability to sell additional on-peak electricity at high prices more than offsets the additional cost of burning natural gas during generation, and conventional CAES devices earn higher net revenues. The opposite is true in the reference locations, where low on-peak prices are frequently lower than the

[6] Because natural gas is used during the generation cycle, a conventional CAES device will store only about 0.72 units of electricity for each unit of electricity generated and sold. An adiabatic CAES device must store about 1.4 units of electricity for each unit of electricity generated and sold (1/Roundtrip Efficiency = 1/0.72 = 1.39). Because of this, a conventional CAES device needs to purchases only about half as much electricity as an adiabatic CAES device: $\left(\frac{Electricity\ Purchase_{Conventional}}{Electricity\ Purchase_{Adiabatic}} = Energy\ Ratio_{Conventional} * Roundtrip\ Efficiency_{Adiabatic} = 0.72 * 0.72 = 0.52 \right)$

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marginal cost of the CAES fuel requirements,[7] and adiabatic CAES systems are frequently able to generate higher net revenues.

Figure 7 shows the mean net revenues projected for a conventional CAES system, along with the equivalent capital cost that these net revenues could support, assuming an 11% capital charge rate. For each region, the lower and upper range of net revenues represents the interannual mean of annual net revenues generated by a CAES device over the evaluated years and in the reference location and in the high value location, respectively. The whisker plots show the range in annual net revenues which can be significantly broader than the range of interannual means. Also shown are the equivalent capital costs, which are calculated by dividing the annual net revenues by the 11% annual capital charge rate [18]. For example, if a CAES device generates an annual net revenue of $55/kW-yr, we estimate an equivalent capital cost of ($55/kW-yr)/(0.11/yr) = $500/kW. While this simplistic approach does not fully capture how utilities decide whether or not to invest in storage resources, it does give a basic estimate of whether the net revenues earned by a device are sufficient to support a capital investment. Figure 7 also shows a range of conventional CAES capital costs from Table 2.

There is significant overlap between the equivalent capital costs and projected CAES capital costs in some regions, which suggests that CAES investments could be supported by historical revenues. However, this analysis supports previous conclusions that arbitrage revenues alone are frequently insufficient to cover capital costs of most storage technologies [1,6]. If additional revenues from capacity payments or other ancillary services revenues such as frequency regulation were captured, it is likely that CAES would be profitable in several additional regions and years. For example, *Sioshansi et al.* [8] use capacity payments in the range of $20 – 60/kW-yr, and *Lund and Salgi* [6] use regulating power market revenues of about $60/kW-yr, which could support an additional CAES capital cost of $200-550/kW, assuming an 11% capital charge rate.

Figure 8 shows a similar projection of net revenues, equivalent capital costs, and cost projections for adiabatic CAES systems. While adiabatic CAES net revenues are similar to conventional CAES net revenues, system costs are likely to be higher (Table 2), and arbitrage and reserves revenues alone do not appear to support a capital investment in most regions. As with conventional CAES, Figure 8 does not include capacity payments, or potential regulation revenues and capturing these additional revenue streams could support investing in an adiabatic CAES systems in several regions. It also does not consider any additional benefits of adiabatic CAES under carbon or other policies effecting the cost or use of natural gas.

Our CAES arbitrage only net revenues are similar to those in recent U.S. studies. For example, arbitrage revenues for a conventional CAES system with 20 hours of storage have been estimated to range from $48-81/kW-yr *Sioshansi et al.* [8] in PJM from 2002-2007. Arbitrage net revenues for a pure storage devices have been estimated at about[8] $55/kW-yr by *Eyer and Corey* [1], and $46-180/kW-yr in NYISO by *Walawalkar et al.* [9]. Our analysis finds generally brackets previous arbitrage net revenue results, with the exception of the high range found by *Walawalkar et al.* [9] that represents arbitrage by a battery or flywheel in New York City. CAES arbitrage revenues from U.S. studies are generally higher than those found in several European studies focusing on electricity markets in Denmark [6,19]. Mean wholesale electricity prices in Denmark are frequently set by hydropower electricity prices and are typically lower

[7] This is discussed in more detail in section 4.1.

[8] Eyer and Corey (2010) estimate $400/kW for 10 years of energy arbitrage, assuming a 2.5% interest rate and a 10% discount rate. This corresponds to mean annual arbitrage revenues of about $55/kW-yr.

than mean U.S. electricity prices. Also, diurnal electricity load and price patterns frequently show lower off- to on-peak differences, particularly in summer because air conditioning loads in northern Europe are negligible. *Lund and Salgi* [6] similarly find that arbitrage revenues alone are not likely to support a CAES investment, but the combination of capacity and arbitrage revenues may be sufficient to support a CAES investment.

4. Sensitivities

Several next generation conventional CAES designs have been proposed to improve operating parameters and reduce capital cost [14]. The economics of new CAES designs with different design and performance parameters are highly dependent on the applications served by each CAES device. In this section we characterize the relationship between CAES net revenues to device efficiencies, expander and compressor design characteristics, and non-optimal dispatch to better understand how optimal CAES design varies based on device type (conventional or adiabatic), dispatch method (co-optimized or arbitrage only), and device location.

4.1. Device Efficiency

Several alternative CAES designs have been proposed, some of which represent a trade-off between capital cost and efficiency (energy ratio and heat rate for conventional CAES; round-trip efficiency for adiabatic/isothermal CAES). Device efficiency mainly affects arbitrage revenues, where a lower efficiency device will need a larger spread between off-and on-peak prices for arbitrage to be profitable. This relationship between device efficiency and profitable electricity dispatch and purchase prices is shown in equation 1 for conventional CAES systems and equation 2 for adiabatic CAES systems:

$$\text{Dispatch Price}_{(\$/MWh)} > \text{Purchase Price}_{(\$/MWh)} * \text{Energy Ratio} + \frac{\text{Natural Gas Price}_{(\$/mmBTU)} * \text{Heat Rate}_{(BTU/kWh)}}{1000} + O\&M \qquad [1]$$

$$\text{Dispatch Price}_{(\$/MWh)} > \frac{\text{Purchase Price}_{(\$/MWh)}}{\text{Roundtrip Efficiency}} + O\&M \qquad [2]$$

Figure 9 represents the relationship between the net revenues generated by conventional and adiabatic CAES systems and device efficiencies. Conventional CAES efficiencies vary with system energy ratio and heat rate (left and middle panels) and adiabatic CAES efficiency is characterized by roundtrip efficiency (right panel). Figure 9 shows relationships calculated for arbitrage only systems, but co-optimized systems have nearly identical relationships. This is because device efficiency mainly affects arbitrage revenues and not reserves revenues, and the results shown in Figure 9 are representative of both arbitrage only and co-optimized CAES systems. Here and elsewhere, sensitivities are characterized by the change in system net revenue, calculated for each region, location, and year. Sensitivities are plotted for each region (shown by color), for both the reference location (solid lines) and the high value location (dashed lines). Interannual variability is represented by standard deviation of sensitivities, and plotted as vertical bars. We were unable to characterize interannual variability in CAISO and MISO since we had only one year of market data.

Figures 9 shows that a 10% improvement in the conventional CAES energy ratio or heat rate could generate an additional \$5/kW-yr in annual net revenues. Here and elsewhere, the additional annual net revenues can be used to estimate the increase in capital cost that these revenues could support by dividing by the an annual capital charge rate of 11% [18]. For example, the additional \$5/kW-yr in annual revenue from a 10% improvement in heat rate or energy ratio could support about a \$45/kW increase in capital cost[9]. The similarity in the sensitivity of net revenues to improving energy ratios or heat rates suggests that improving one at the sacrifice of the other would not improve device economics. For example, if a new device were designed that had a 10% lower energy ratio but a 10% higher heat rate, the difference in net revenues generated by the device would be negligible, and the device would have to cost less to improve system economics.

Adiabatic CAES net revenues are more sensitive to improved round trip efficiency, where a similar 10% improvement in round trip efficiencies increases annual net revenues by about \$10/kW-yr. The additional net revenue could support higher device costs of about \$91/kW. Increasing adiabatic round trip efficiencies has about twice as much impact as increasing conventional heat rates or energy ratios independently, because conventional CAES performance depend on both.

4.2. Energy Storage Capacity

In the reference results, CAES energy storage capacity (MWh) was assumed to be 20 hours times peak expander output (MW). However, given constraints on geologic formations, and the possibility of using above ground storage, it may be more economic to deploy CAES with lower storage capacity. Figure 12 shows the relationship between CAES net revenue and the number of hours of energy storage. The sensitivities are nearly identical for co-optimized and arbitrage only systems, suggesting that energy storage capacity primarily affects arbitrage revenues. The increase in net revenue with additional storage capacity beyond 20 hours is small – increasing storage capacity from 20 to 40 hours increases net revenues by less than \$5/kW-yr for all systems except the high value location in MISO which increases by about \$10/kW-yr. Also, decreasing from 20 hours down to 12 hours has a similarly small impact on net revenues which decrease by less than \$5/kW-yr in nearly all regions. However, decreasing storage capacity to less than 10 hours significantly reduces system net revenues. For example, a system with 4 hours of storage earns \$20-30/kW-yr less per year relative to a system with 20 hours of storage for a device located in a high value location, and about \$5-10/kW-yr less per year for a device located in the reference regions. This suggests that the net revenues earned by increasing storage capacity from 4 to 10 hours is \$45-90/kW in the reference locations, and \$180-270/kW in high value locations. The large decrease in arbitrage revenues below about 10 hours of storage is similar to results found previously in PJM [10].

4.3. Expander and Compressor Sizes

CAES compressors and expanders can be sized independently to optimize device economics. For example, the McIntosh CAES plant has an oversized expander (110 MW) relative to its compressor (81

[9] Additional Capacity Cost (\$/kW) = Additional Annual Revenue (\$/kW-yr) / Expected Annual Return on Investment (1/yr) = \$5/kW-yr/0.11/yr = \$45.5/kW.

MW), as does the proposed Norton CAES plant (300MW expander and 200MW compressor). Since conventional CAES systems store less energy than they discharge because they burn natural gas, conventional CAES designs frequently have oversized expanders so the device can spend a similar amount of hours charging and discharging. The converse is true for adiabatic systems, which store more energy than they discharge because of efficiency losses, and adiabatic systems have been proposed with oversized compressors [14]. Here we explore the relative economics of sizing CAES compressors and expanders, and evaluate how this varies with device type (conventional or adiabatic), grid applications provided by the system, and device location.

Increasing expander and compressor sizes increases CAES operational revenues, but it also increases CAES capital costs. To determine whether the added revenues outweigh costs, we use component level CAES estimates from EPRI [14], summarized in Table 4. The relationships used to estimate the increase in system costs based on increased component sizes are outlined in the appendix. Relative CAES economics are characterized using relative return on investment (ROI), defined as follows:

$$Relative\ ROI = \frac{\left(\dfrac{System\ Net\ Revenue_2}{System\ Cost_2}\right)}{\left(\dfrac{System\ Net\ Revenue_1}{System\ Cost_1}\right)} \quad [3]$$

Relative ROIs that are greater than one represent CAES configurations where the increase in net revenue was greater than the associated increase in cost. Conversely, relative ROIs that are less than one represent a configuration where additional costs exceed additional revenues.

Figure 11 shows the relative economics of oversizing conventional CAES expanders. Doubling CAES expanders sizes relative to the compressor increases annual revenues by about $25-50/kW-yr for co-optimized systems and by about $10/kW-yr for arbitrage only systems. The increase is higher in some regions, namely the high value locations in NYISO and MISO. When the added revenue is combined with increased costs, co-optimized systems could increase their relative ROIs by about 30-50%, and arbitrage only systems could increase their relative ROIs by about 10-20%. There is a distinct flattening in the relationship between relative ROIs for arbitrage only systems beyond a 50% oversized expander, but the co-optimized net revenues continue to increase with increasing expander sizes. For example, increasing the expander size from 50% oversized to 100% oversized would increase relative ROIs by 3% in the reference location in PJM. Because these relationships become relatively flat, or continue to increase, there is no clear optimum expander size for conventional systems. Figure 11 shows that co-optimized systems are far more sensitive to expander size than arbitrage only Larger expanders are more valuable to co-optimized systems because reserves are primarily a capacity resource, and doubling expander size approximately doubles system capacity and reserves revenues. Arbitrage only revenues also increase with larger expander sizes because more electricity can be sold during the hours with the highest prices. This increases sales revenue, and increases the number of hours when energy arbitrage is profitable (Equation 1). Co-optimized adiabatic CAES systems also show increased relative ROIs with increasing expander sizes, based on increasing reserve revenues. However, this increase is less than for conventional CAES systems and a representative relationship from NYISO in 2007 is shown in Figure 13.

Figure 12 shows the relative economics of oversizing adiabatic CAES compressors. Doubling CAES compressor sizes relative to the expander increases annual revenues by about $10-20/kW-yr for both co-optimized and arbitrage only systems. When the added revenue is combined with increased costs, co-optimized systems could increase their relative ROIs by about 10-20%, and arbitrage only systems could increase their relative ROIs by about 10-30%. The fractional increase is more for arbitrate only systems, because the added net revenue is about the same for both co-optimized and arbitrage only systems but the reference revenue is significantly less for arbitrage only systems. The increase in relative ROIs with compressor size flattens around for compressor increases above 50-100% for co-optimized systems, and for increases from 100-150% for arbitrage only systems. Because these curves become relatively flat, there is no clear optimum compressor size for adiabatic systems.

Figures 11 and 12 show the relative economics of increasing expander and compressor sizes independently for conventional and adiabatic systems. However, without exploring the relative economics of several expander and compressor size configurations, it is challenging to determine the most effective strategy for sizing of each component. Figure 13 shows contour plots of relative CAES net revenues for conventional and adiabatic systems with co-optimized and arbitrage only dispatches for the reference location in NYISO in 2007[10]. These show relative CAES net revenues over a large surface space of component configurations, and helps illustrate how best to size components. In these figures, energy storage capacity (MWh) was held fixed, and the number of hours of energy storage effectively decreases with increasing expander capacity.

Figure 13 shows relative CAES economics over the full surface space of expander and compressor sizes, not just individual perturbations to expander size (Figure 13) or compressor size (Figure 14). For the reference region in NYISO in 2007, there are strong trends for oversizing the expander for co-optimized conventional and adiabatic systems. This is for reasons described earlier – the oversized expander pays for itself by providing more operating reserves. There is also a strong trend for oversizing the compressor in an adiabatic arbitrage only device. There is no clear trend to oversize the expander on a conventional CAES system.

4.4. Minimum expander output

In Figures 11 through 13, the minimum operating limit for the expander and compressor was defined as 20% of the maximum output. Spinning reserve revenues are primarily earned when the storage device operates at minimum generation and sells the difference between minimum operating capacity and maximum generation capacity (Figure 1). Spinning reserve revenues can be increased by increasing the expander size (Figures 11 and 13) or by decreasing the minimum expander output.

[10] CAES performance in 2007 in the reference location in NYISO most closely represented the 8 year NYISO mean, and is used here to illustrate mean performance trends.

Figure 14 shows the relationship between CAES net revenues and the minimum expander output, characterized by the fraction of maximum output capacity. Reducing the minimum expander output from 20% to 10% of the maximum output increases co-optimized CAES net revenues by about $2-6/kW-yr. Doubling the minimum expander output to 40% decreases co-optimized net revenues by $5-10/kW-yr. It is unclear how CAES capital and operations costs would increase to support lower minimum expander output limits, but the added net revenue could support about an additional $20-55/kW in capital costs.

The sensitivity of net revenues to minimum expander limits are similar for conventional and adiabatic CAES systems, primarily because reserves revenues are mostly sensitive to capacity and far less sensitive to differences in device efficiency and operating characteristics. Arbitrage only systems are not sensitive to minimum expander (or compressor) limits, because arbitrage only devices typically operate at maximum charge or discharge during the hours when it is economic to operate in either mode.

4.5. Sensitivity to imperfect foresight

In the analysis above, we assume that day-ahead energy and reserves prices are know with perfect foresight, and the CAES devices are optimally dispatched to these prices. Because future day-ahead energy and reserves prices are not known with perfect foresight, the net revenues presented above represent an upper bound. To evaluate the impact of the imperfect foresight, we calculate CAES net revenues using a non-optimal “back-casting” approach, following Sioshansi et al. [10]. This method simply applies an optimal dispatch from a prior period to one in the future, assuming price patterns are similar over short time periods (from day to day, or from one week to the next). This method is meant to provide a lower bound on the impact of the imperfect foresight of prices, since there are more sophisticated methods for estimating near-term electricity demand and prices.

Table 5 shows the fraction of optimal CAES net revenues captured using the back-casting technique with a one day time lag. Interannual mean values are shown for NYISO and PJM. We did not include the 2009 back-casting results for MISO and CAISO because they did not appear to be representative of multi-year performance. Considerable value is captured using the back-casting technique for all dispatch strategies and locations because electricity prices have fairly consistent daily and seasonal patterns [8,10,19]. Co-optimized systems capture a higher fraction of optimal net revenues using the back-casting technique. This is because reserve prices are relatively constant over most days, and the timing of when to dispatch for reserves revenues is less sensitive than timing the extremes in off- and on-peak prices for energy arbitrage. The worst performance is seen for conventional CAES devices dispatched for energy arbitrage in the reference locations, where they capture about two thirds of the value of optimally dispatched devices. The back-casting technique captures a higher percentage of optimal net revenues in the high value locations, likely because the spreads between off- and on-peak prices are higher and it is not as critical to time the exact hours when arbitrage is profitable.

5. Conclusions

Storage devices can provide several grid services, and here we quantify the value of dispatching CAES to provide operational reserves in addition to energy arbitrage. We find that providing operating reserves increases annual net CAES revenues by $23 ± 10/kW-yr for conventional devices, and $28 ± 13/kW-yr for adiabatic devices. Energy arbitrage and operating reserves net revenues could make conventional CAES devices profitable in several electricity markets, but adiabatic CAES devices would likely need additional revenue streams to be profitable. These could include capacity payments or other capacity-based revenue streams that were not included in this analysis.

The optimal allocation of storage resources to provide operational reserves and energy arbitrage has mean seasonal trends, but can shift significantly on weekly time scales, and from one year to the next, based on market conditions. CAES resources need to be dynamically allocated at these short time scales to capture the full value provided by storage devices.

CAES devices can be designed to have a wide range of operational parameters, including different expander (energy generation capacity) and compressor (energy storage capacity) sizes, system efficiencies, stored energy capacities, and system operational characteristics. We find that varying these parameters primarily affects arbitrage revenues (energy resource) and not reserve revenues or other capacity-based revenue streams. Because of this, optimal CAES design is likely to be independent of dispatch strategy. The one exception to this is the relative sizing of the CAES expander, which directly impacts the amount of capacity that can be sold into spinning reserve markets, or other capacity-based markets. We find that it is economic to oversize the expander for co-optimized systems, and optimal for arbitrage only systems to have similarly sized expanders and compressors.

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We thank Eric Ela, Ross Guttromson, Thomas Jenkin, and Michael Milligan for comments.

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Appendix A: Model Formulation

A.1. Model Parameters

T: set of hours in planning horizon;

κ^C: power capacity of CAES compressor (MW);

κ^E: power capacity of CAES expander (MW);

h: hours of storage in CAES facility;

η: roundtrip storage efficiency of CAES system;

r: heat rate of CAES expander (GJ/MWh);

s^C: startup cost of CAES compressor (\$);

s^E: startup cost of CAES expander (\$);

v^E: variable operating cost of CAES expander (\$/MWh);

μ^C: minimum load of CAES compressor (MW);

μ^E: minimum load of CAES expander (MW);

p_t^{en}: price of energy in hour t (\$/MWh);

p_t^{sp}: price of spinning reserves in hour t (\$/MW-h);

p_t^{ns}: price of non-spinning reserves in hour t (\$/MW-h); and

p_t^{ng}: price of natural gas in hour t (\$/GJ).

A.2. Model Variables

l_t: storage level of CAES facility at end of hour t (MWh);

σ_t: energy stored in hour t (MWh);

d_t: energy discharged in hour t (MWh);

n_t: net energy sales in hour t (MWh);

u_t^C : binary variable indicating whether CAES compressor is online in hour t;

u_t^E : binary variable indicating whether CAES expander is online in hour t;

a_t^C : binary variable indicating whether CAES compressor is started up in hour t;

a_t^E : binary variable indicating whether CAES expander is started up in hour t;

A.3. Model Formulation

$$\max \sum_{t \in T} \big[p_t^{en} n_t + p_t^{sp} \cdot (\sigma_t + \kappa^E - n_t) - (p_t^{sp} - p_t^{ns})\kappa^E \cdot (1 - u_t^E) \quad (1)$$
$$-(p_t^{ng} r + v^E) d_t/\eta - s^C a_t^C - s^E a_t^E\big]$$

$$\text{s.t.} \quad n_t = d_t/\eta - \sigma_t, \qquad \forall\, t \in T \quad (2)$$
$$l_t = l_{t-1} + \sigma_t - d_t, \qquad \forall\, t \in T \quad (3)$$
$$\mu^C u_t^C \le \sigma_t \le \kappa^C e_t^C, \qquad \forall\, t \in T \quad (4)$$
$$\mu^E u_t^E \le d_t/\eta \le \kappa^E u_t^E, \qquad \forall\, t \in T \quad (5)$$
$$a_t^C \ge u_t^C - u_{t-1}^C, \qquad \forall\, t \in T \quad (6)$$
$$a_t^E \ge u_t^E - u_{t-1}^E, \qquad \forall\, t \in T \quad (7)$$
$$u_t^C + u_t^C \le 1, \qquad \forall\, t \in T \quad (8)$$

The objective function (1) maximizes net revenue from energy and ancillary service sales. The model assumes that CAES can only provide spinning reserves when it is online. When the compressor is online, CAES can provide spinning reserves equal to the amount of energy that is being charged (σ_t), by shutting the compressor off. If the expander is online, then it can provide spinning reserves equal to unused expander capacity ($\kappa^E - n_t$) by increasing the output of the expander. When it is offline, it can provide non-spinning reserves equal to the expander capacity. Constraint (2) defines net sales in terms of the amount of energy charged and discharged. Constraint (3) defines the storage level in each hour in terms of the previous hour's storage level and charging and discharging decisions. Constraints (4) and (5) define upper and lower bounds on the compressor and expander, respectively. Constraints (6) and (7) define the startup variables in terms of the online variables. Constraint (8) imposes the restriction that the compressor and expander cannot be online simultaneously.

Appendix B: Additional model assumptions and results

Table B.1. Historical market data used in this analysis

Market	Years with data	Market Price	Location	Energy Price Location	Synchronized Reserves Location	Operating Reserves Location
CAISO	**2009 - 2010**	Low	Kern Co (PGE)	KERN_PWR_1_B1 node	AS_CAISO_EXP price	AS_CAISO_EXP price
		High	Anaheim, CA	ANAHEIM_6_N001 node		
MISO	**2009**	Low	Iowa Stored Energy Park	ALTW.OTTUMW1 node	MISO price	MISO price
		High	Upper Michigan	NIPS.MICHCP2 node		
NYISO	**2002-2009**	Low	NYSEG (Central NY)	Central Zone price	West Reserve Price	West Reserve Price
		High	Long Island, NY	Long Island Zone price	East Reserve Price	East Reserve Price
PJM	**2005-2009**	Low	Norton (Central Ohio)	AEP Zonal Price	Western (2005-2006); RFC (2007-2009)	PJM Operating Reserve (Daily Price for DA market)
		High	PSEG	PSEG Zonal Price	Mid-Atlantic (2005-2006);	

					RFC (2007-2009)	

CAES net revenues are driven by interannual price variations, regional price differences, and device operation strategies. Tables A.2 and A.3 illustrate how these variations impact the gross revenues and operating costs that underlie the net revenues generated by CAES devices.

Table B.2. Net revenues for Conventional CAES systems ($2009 US dollars)[1]

			Co-optimized				**Arbitrage Only**			**Market Data**	
Region	**Year**	**Location**	**Net Revenue ($/kW-year)**	**Arbitrage Revenue ($/kW-year)**	**Reserves Revenue ($/kW-year)**	**Operating Cost ($/kW-year)**	**Net Revenue ($/kW-year)**	**Arbitrage Revenue ($/kW-year)**	**Operating Cost ($/kW-year)**	**Mean Electricity Price ($/MWh)**	**Mean Natural Gas Price ($/GJ)[2]**
CAISO	**2009-2010**	Reference	43	116	24	97	23	121	98	36	4.2
		High Value	50	134	24	108	30	140	110	37	
MISO	**2009**	Reference	37	59	24	46	21	80	60	23	4.5
		High Value	96	177	24	105	79	200	120	44	
NYISO	**2002**	Reference	53	122	22	91	33	128	95	39	3.9
		High Value	109	243	22	155	89	249	160	57	
	2003	Reference	61	171	31	140	35	183	148	55	6.0
		High Value	109	308	28	227	85	326	241	73	
	2004	Reference	37	153	15	131	26	163	137	55	6.4
		High Value	66	268	13	214	57	286	229	72	
	2005	Reference	61	199	30	167	42	241	200	77	8.9
		High Value	135	363	43	270	106	445	339	109	
	2006	Reference	55	109	41	96	27	161	134	58	7.6
		High Value	147	284	44	181	115	354	240	91	
	2007	Reference	58	156	30	128	37	194	157	61	7.8
		High Value	145	352	29	236	124	414	290	89	
	2008	Reference	51	129	39	116	25	150	124	68	10.0
		High Value	159	391	52	284	118	459	341	100	
	2009	Reference	33	52	28	47	12	73	61	36	5.1
		High Value	84	193	27	136	62	224	162	50	
	Mean	Reference	51	136	29	115	33	176	144	56	-
		High Value	119	300	32	213	102	372	270	80	
PJM	**2005**	Reference	49	178	3	132	47	179	132	53	10.1
		High Value	139	296	56	213	98	335	237	75	
	2006	Reference	37	135	4	102	34	138	104	44	7.8
		High Value	102	185	59	141	60	226	167	57	
	2007	Reference	89	185	48	144	53	198	145	47	8.2
		High Value	123	279	48	204	85	296	210	66	
	2008	Reference	71	190	31	151	49	194	145	54	10.3
		High Value	113	327	31	245	89	341	252	80	
	2009	Reference	33	56	31	54	11	62	51	33	4.7
		High Value	50	114	30	94	28	138	110	42	
	Mean	Reference	58	155	24	121	39	154	115	46	-
		High Value	110	250	47	187	72	267	195	64	

[1]All values are rounded to the nearest dollar, and do not always add exactly.
[2]Natural gas markets in the United States typically use price units of $/mmBTU, and the price conversion to GJ was calculated based on 1 mmBTU = 1.055 GJ.

Table B.3. Net revenues for Adiabatic CAES systems ($2009 US dollars)[a]

			Co-optimized				**Arbitrage Only**			**Market Data**	
Region	**Year**	**Location**	**Net Revenue**	**Arbitrage Revenue**	**Reserves Revenue ($/kW-**	**Operating Cost ($/kW-**	**Net Revenue ($/kW-**	**Arbitrage Revenue ($/kW-**	**Operating Cost ($/kW-**	**Mean Electricity Price**	**Mean Natural Gas Price**

			($/kW-year)	($/kW-year)	year)	year)	year)	year)	year)	($/MWh)	($/GJ)[2]
CAISO	**2009-2010**	Reference	38	73	26	61	16	67	51	36	4.2
		High Value	42	84	26	68	20	79	58	37	
MISO	**2009**	Reference	53	66	24	37	36	80	45	23	4.5
		High Value	79	136	26	84	60	141	82	44	
NYISO	**2002**	Reference	48	87	25	64	26	84	58	39	3.9
		High Value	82	150	25	94	59	148	89	57	
	2003	Reference	63	121	34	92	34	120	86	55	6.0
		High Value	80	173	33	125	52	170	118	73	
	2004	Reference	41	113	17	89	29	114	85	55	6.4
		High Value	46	140	16	110	34	138	104	72	
	2005	Reference	64	152	33	121	40	165	125	77	8.9
		High Value	94	216	53	175	57	222	165	109	
	2006	Reference	62	102	42	82	31	128	98	58	7.6
		High Value	114	186	51	123	77	194	117	91	
	2007	Reference	63	126	35	97	37	141	104	61	7.8
		High Value	109	205	40	137	78	214	136	89	
	2008	Reference	63	128	40	106	33	138	105	68	10.0
		High Value	132	234	65	167	78	247	169	100	
	2009	Reference	37	51	28	43	14	62	49	36	5.1
		High Value	71	120	34	84	41	127	85	50	
	Mean	Reference	55	110	32	87	30	119	89	56	-
		High Value	91	178	40	127	60	182	123	80	
PJM	**2005**	Reference	102	229	3	130	100	231	131	53	10.1
		High Value	180	275	69	163	123	291	168	75	
	2006	Reference	61	152	4	94	58	153	95	44	7.8
		High Value	125	171	67	113	69	191	121	57	
	2007	Reference	128	175	52	99	83	187	104	47	8.2
		High Value	125	205	52	132	80	211	131	66	
	2008	Reference	111	188	35	112	82	195	113	54	10.3
		High Value	107	236	35	164	79	234	155	80	
	2009	Reference	39	60	30	51	15	67	52	33	4.7
		High Value	49	86	32	70	23	95	72	42	
	Mean	Reference	88	161	25	97	67	166	99	46	-
		High Value	117	195	51	128	75	204	130	64	

[1]All values are rounded to the nearest dollar, and do not always add exactly.

[2]Natural gas markets in the United States typically use price units of $/mmBTU, and the price conversion to GJ was calculated based on 1 mmBTU = 1.055 GJ.

Figure Captions:

Figure 1. CAES operating modes for a device that provides energy arbitrage and ancillary services.

Figure 2. Representative CAES dispatch for a system optimized for energy arbitrage only and for a co-optimized system.

Figure 3. Conventional CAES dispatch characteristics in two NYISO locations for systems dispatched for energy arbitrage only (Arb) and for co-optimized systems (Co-Opt).

Figure 4. Mean CAES discharge characteristics for co-optimized conventional and adiabatic CAES systems simulated in NYISO from 2002-2009. Mean CAES discharge frequencies represent the fraction of time spent in partial or full discharge for each in two week periods.

Figure 5. Annual net revenue generated by co-optimized conventional and adiabatic CAES devices (y-axis), relative to the annual net revenue generated by associated arbitrage-only CAES systems (x-axis). Here and elsewhere, annual net revenues are expressed in 2009 U.S. dollars[11].

Figure 6. Annual net revenue from conventional CAES systems relative to adiabatic CAES systems. Each point represents both the revenue generated by an adiabatic system (x-axis) and a conventional system (y-axis). The 1:1 net revenue line is shown by a dashed black line.

Figure 7. Conventional CAES annual net revenues (top axis) and the equivalent CAES capital cost (bottom axis) that could be supported by these revenues assuming an 11% capital charge rate. The colored bars represent the range in mean net revenues, where the lower bound represents the interannual mean net revenue for a CAES device in the reference location and the upper bound represents the interannual mean for a CAES device in the high value location. The whisker plots represent the range in annual net revenues for each region.

Figure 8. Adiabatic CAES annual net revenues (top axis) and the equivalent CAES capital cost (bottom axis) that could be supported by these revenues assuming an 11% capital charge rate. The colored bars represent the range in mean net revenues, where the lower bound represents the interannual mean net revenue for a CAES device in the reference location and the upper bound represents the interannual mean for a CAES device in the high value location. The whisker plots represent the range in annual net revenues for each region.

Figure 9. Relationship between CAES efficiency parameters and additional net revenues for arbitrage only systems. Relationship for each region are shown by color for both the reference locations (solid lines) and the high value locations (dotted lines).

[11] Net revenues are adjusted to 2009 dollars using historical Consumer Price Index data.

Figure 10. Sensitivity of conventional CAES and adiabatic CAES net revenues to hours of storage. The sensitivity for each region in shown by color, the reference locations are shown by solid lines, and the high value locations are shown by dashed lines.

Figure 11. Sensitivity of conventional CAES economics to over sizing the expander. The sensitivity for each region in shown by color, the reference locations are shown by solid lines, and the high value locations are shown by dashed lines.

Figure 12. Sensitivity of net revenue to relative compressor size. The sensitivity for each region is shown by color, the reference locations are shown by solid lines, and the high value locations are shown by dashed lines.

Figure 13. Contour plots showing the relationship between relative returns on investment (ROIs) and expander and compressor sizes, based on CAES performance in the reference region in NYISO in 2007. The black squares show a 100%:100% expander to compressor relationship.

Figure 14. Additional net revenue as a function of minimum expander output. The sensitivity for each region in shown by color, the reference locations are shown by solid lines, and the high value locations are shown by dashed lines.

Figures:

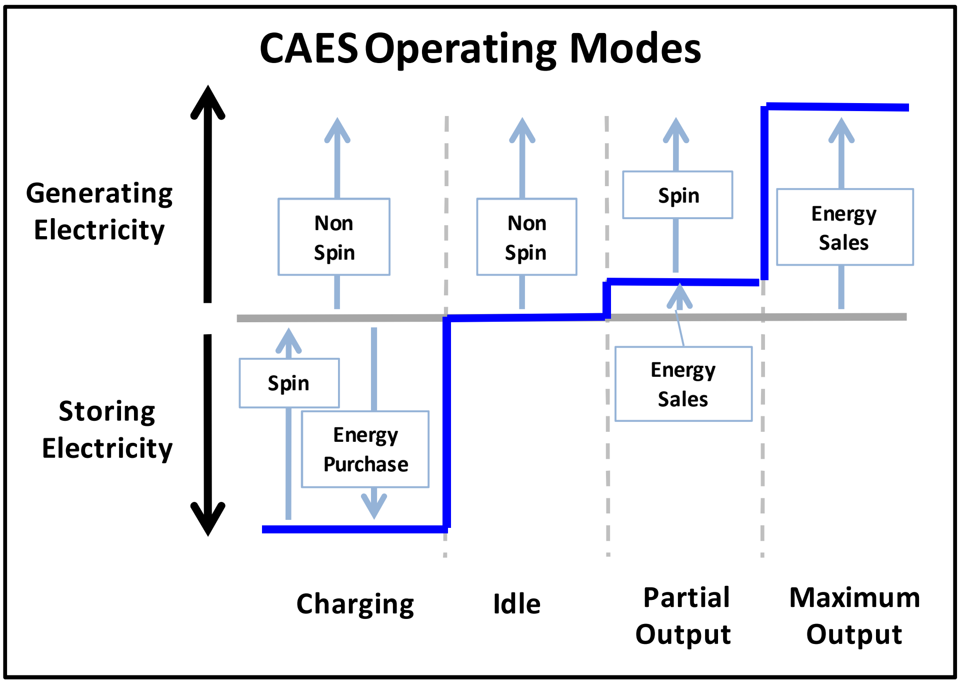

Figure 1. CAES operating modes for a device that provides energy arbitrage and ancillary services.

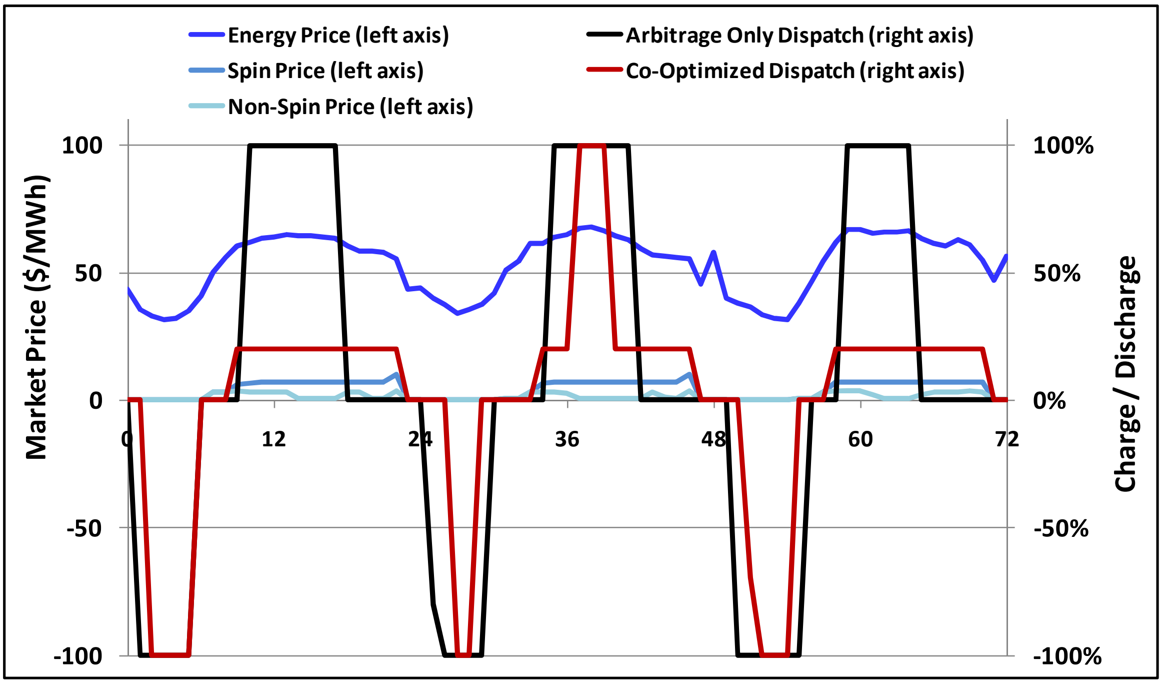

Figure 2. Representative CAES dispatch for a system optimized for energy arbitrage only and for a co-optimized system.

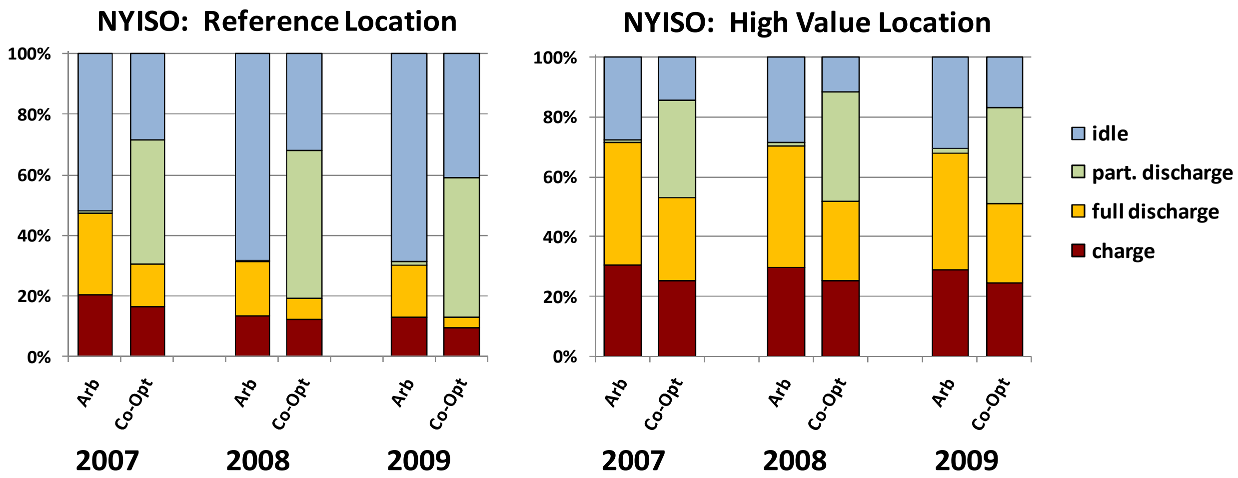

Figure 3. Conventional CAES dispatch characteristics in two NYISO locations for systems dispatched for energy arbitrage only (Arb) and for co-optimized systems (Co-Opt).

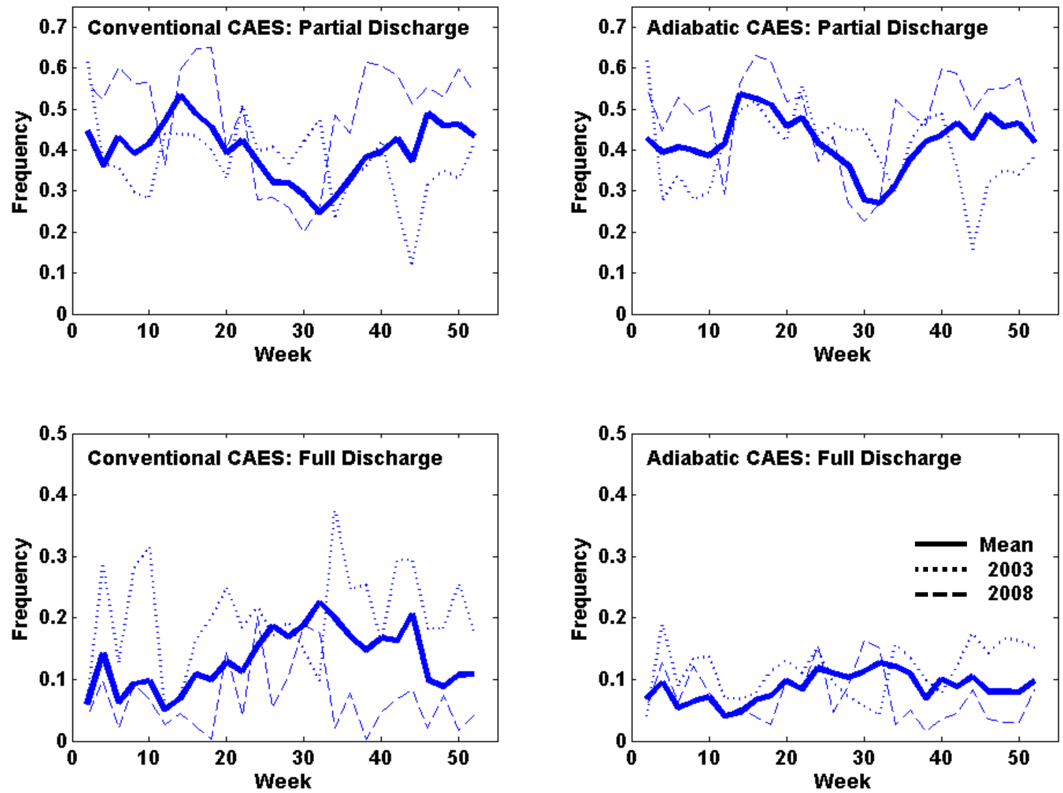

Figure 4. Mean CAES discharge characteristics for co-optimized conventional and adiabatic CAES systems simulated in NYISO from 2002-2009. Mean CAES discharge frequencies represent the fraction of time spent in partial or full discharge for each in two week periods.

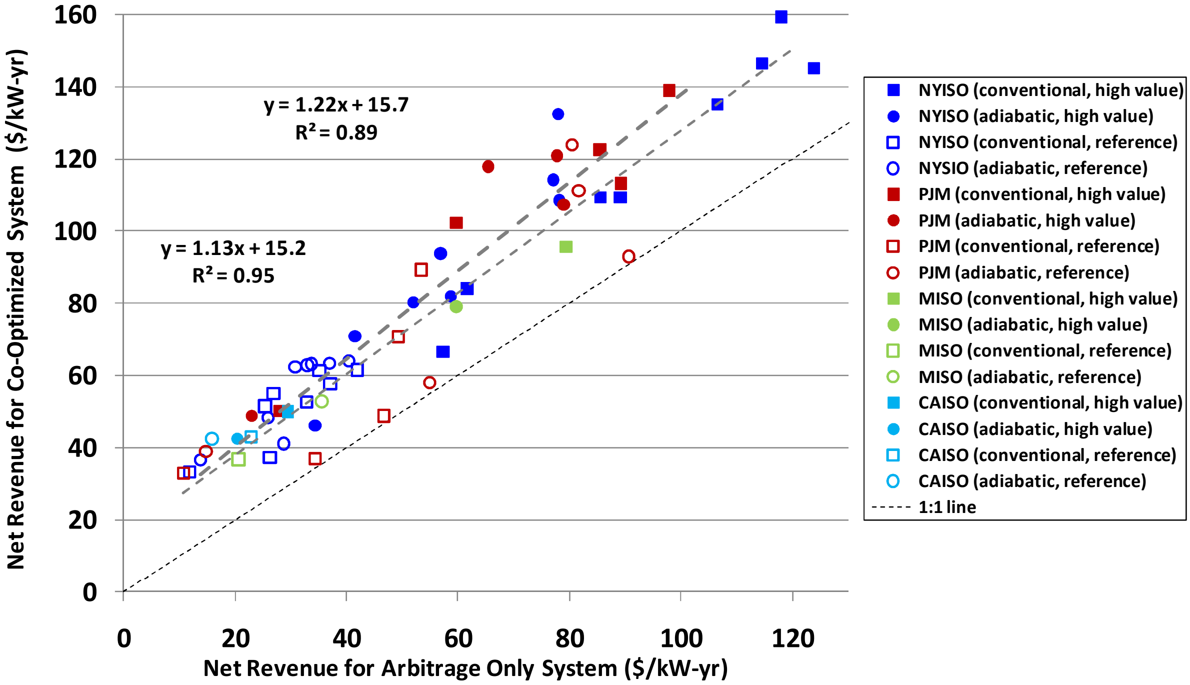

Figure 5. Annual net revenue generated by co-optimized conventional and adiabatic CAES devices (y-axis), relative to the annual net revenue generated by associated arbitrage-only CAES systems (x-axis). Here and elsewhere, market acronyms refer to those listed in Table 1 and annual net revenues are expressed in 2009 U.S. dollars[12].

[12] Net revenues are adjusted to 2009 dollars using historical Consumer Price Index data.

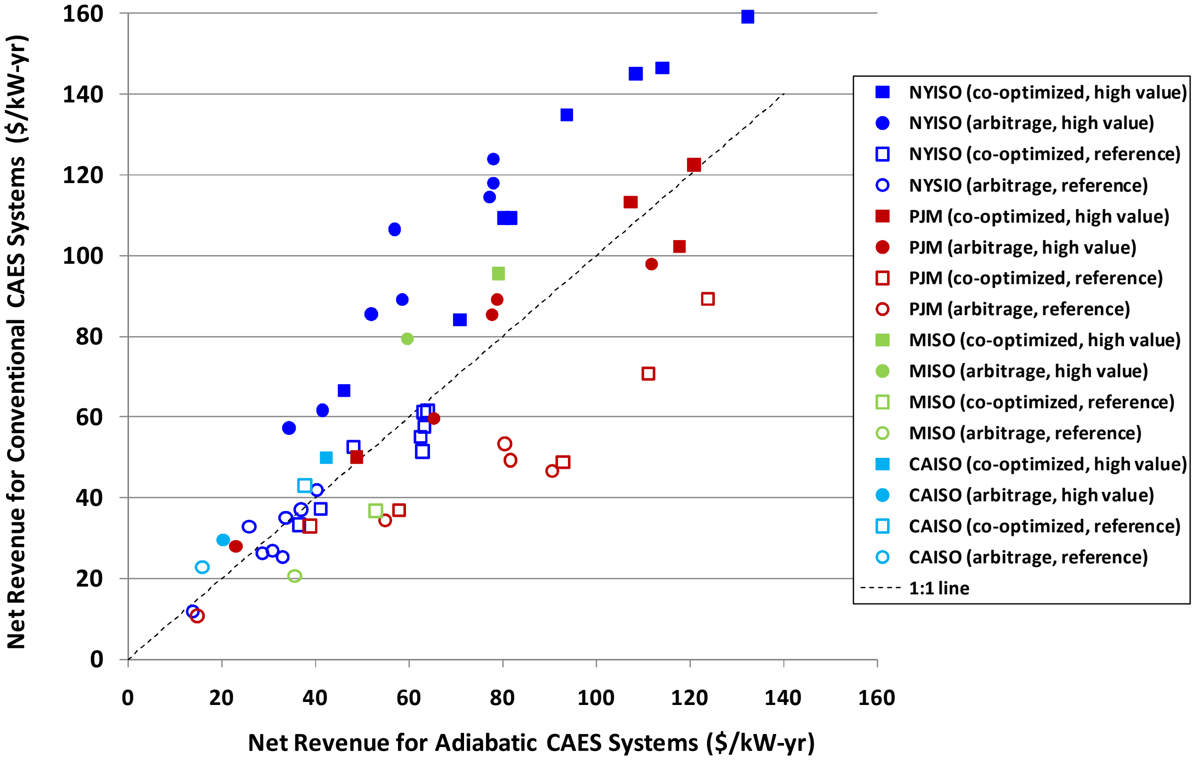

Figure 6. Annual net revenue from conventional CAES systems relative to adiabatic CAES systems. Each point represents both the revenue generated by an adiabatic system (x-axis) and a conventional system (y-axis). The 1:1 net revenue line is shown by a dashed black line.

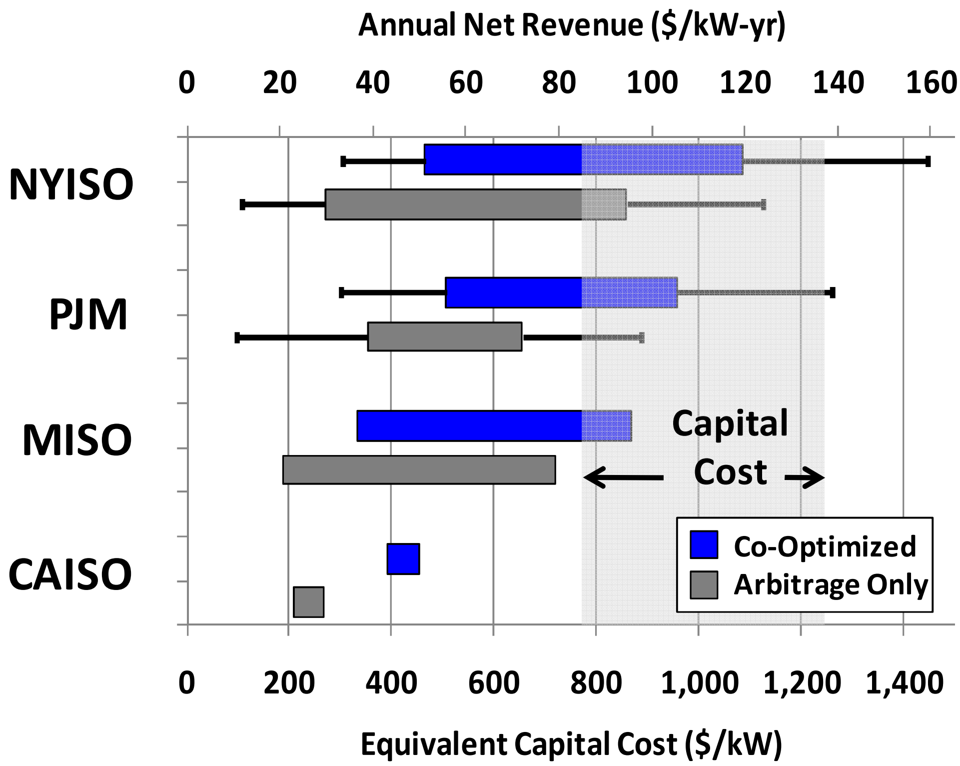

Figure 7. Conventional CAES annual net revenues (top axis) and the equivalent CAES capital cost (bottom axis) that could be supported by these revenues assuming an 11% capital charge rate. The colored bars represent the range in mean net revenues, where the lower bound represents the interannual mean net revenue for a CAES device in the reference location and the upper bound represents the interannual mean for a CAES device in the high value location. The whisker plots represent the range in annual net revenues for each region.

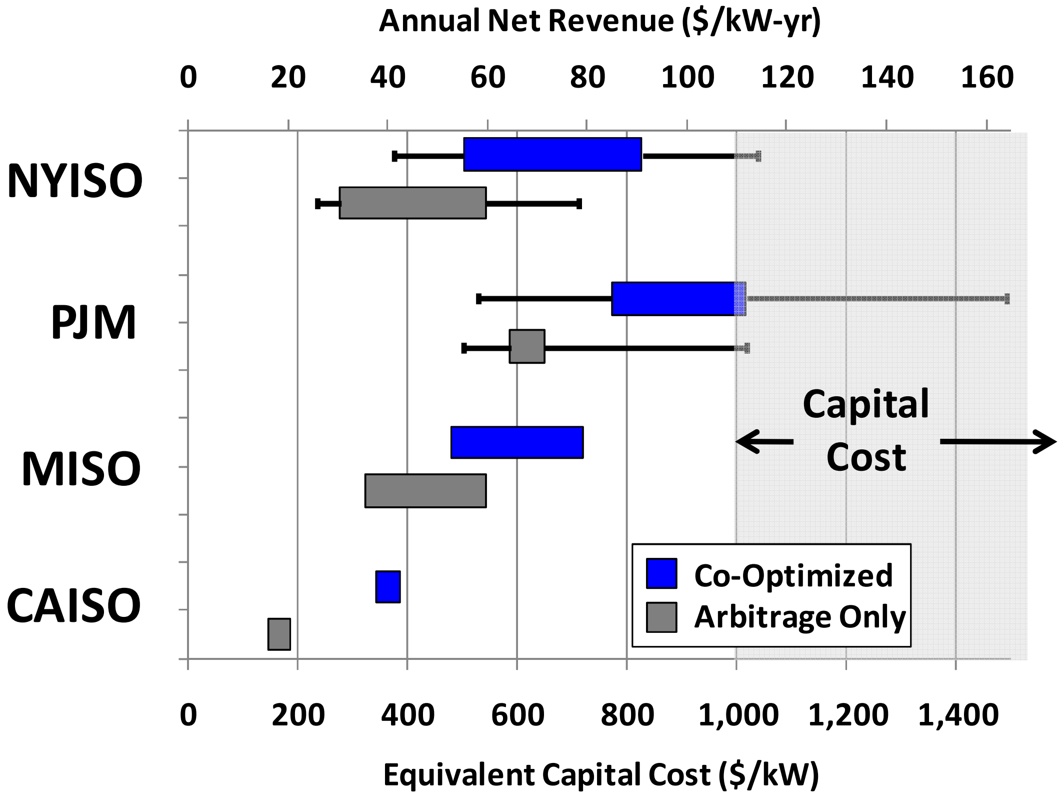

Figure 8. Adiabatic CAES annual net revenues (top axis) and the equivalent CAES capital cost (bottom axis) that could be supported by these revenues assuming an 11% capital charge rate. The colored bars represent the range in mean net revenues, where the lower bound represents the interannual mean net revenue for a CAES device in the reference location and the upper bound represents the interannual mean for a CAES device in the high value location. The whisker plots represent the range in annual net revenues for each region.

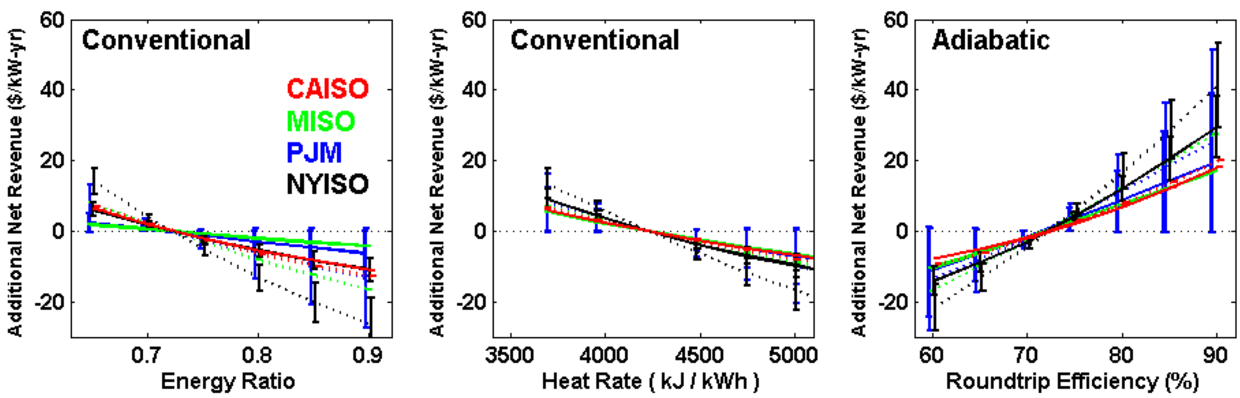

Figure 9. Relationship between CAES efficiency parameters and additional net revenues for arbitrage only systems. Relationship for each region are shown by color for both the reference locations (solid lines) and the high value locations (dotted lines).

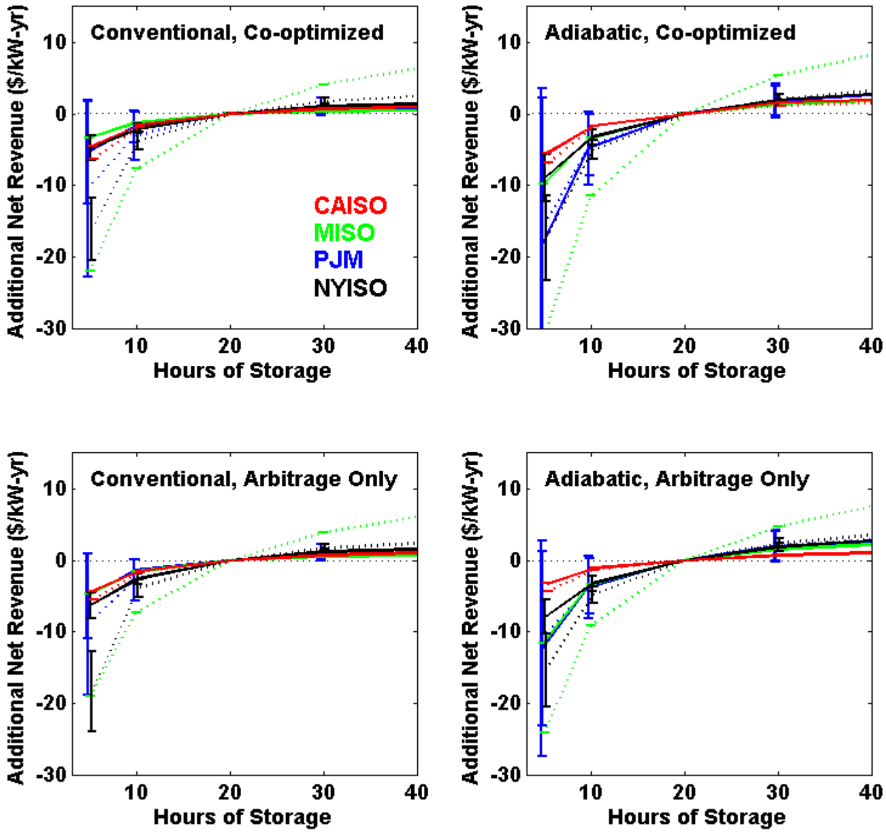

Figure 10. Sensitivity of conventional CAES and adiabatic CAES net revenues to hours of storage. The sensitivity for each region in shown by color, the reference locations are shown by solid lines, and the high value locations are shown by dashed lines.

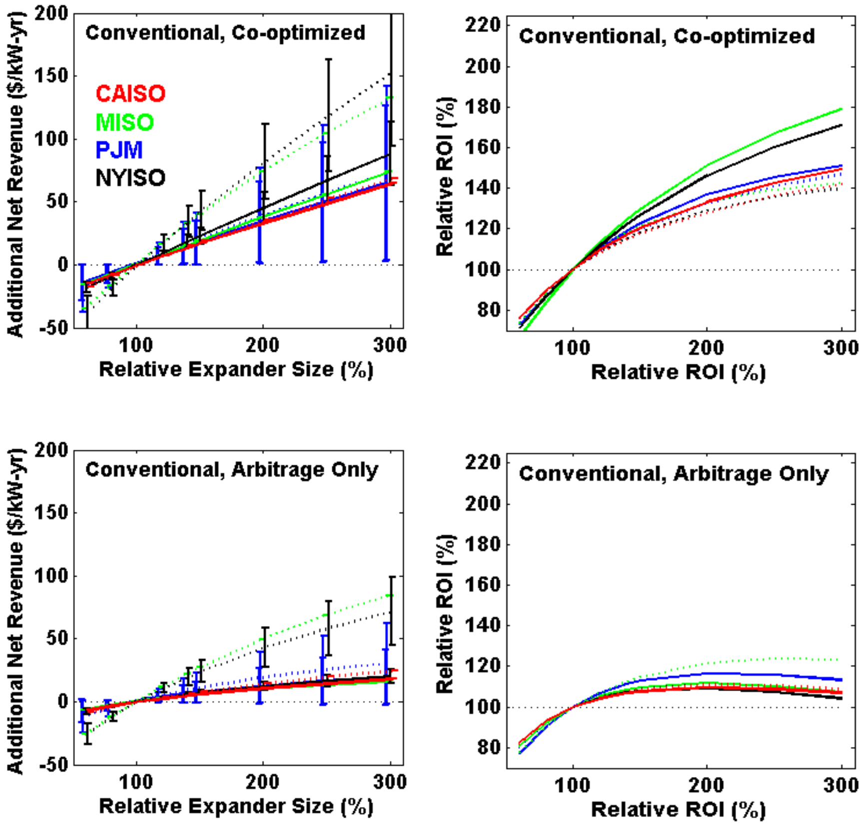

Figure 11. Sensitivity of conventional CAES economics to over sizing the expander. The sensitivity for each region in shown by color, the reference locations are shown by solid lines, and the high value locations are shown by dashed lines.

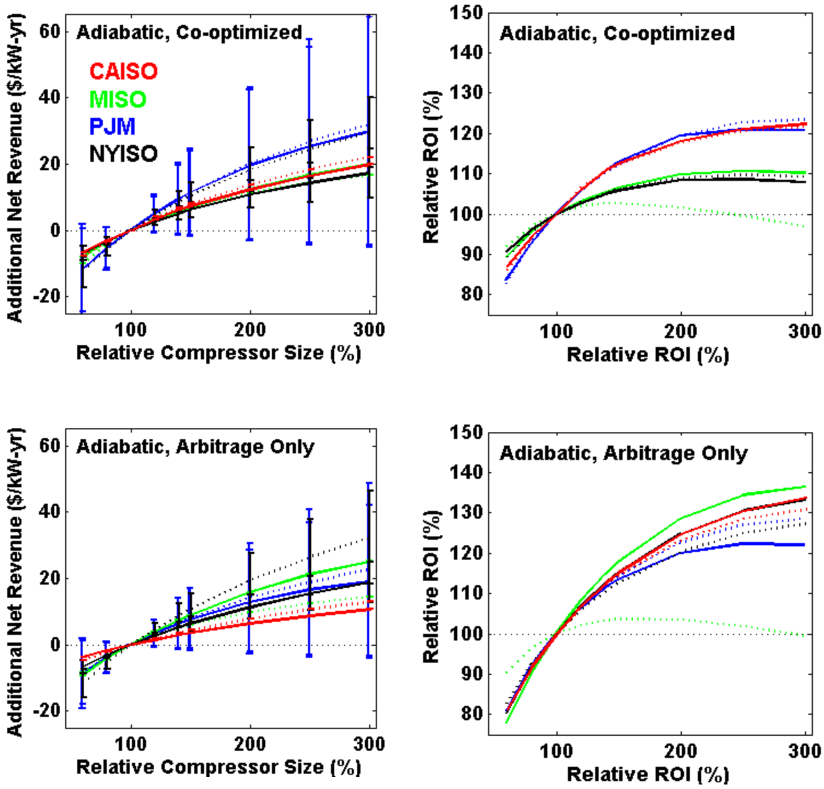

Figure 12. Sensitivity of net revenue to relative compressor size. The sensitivity for each region is shown by color, the reference locations are shown by solid lines, and the high value locations are shown by dashed lines.

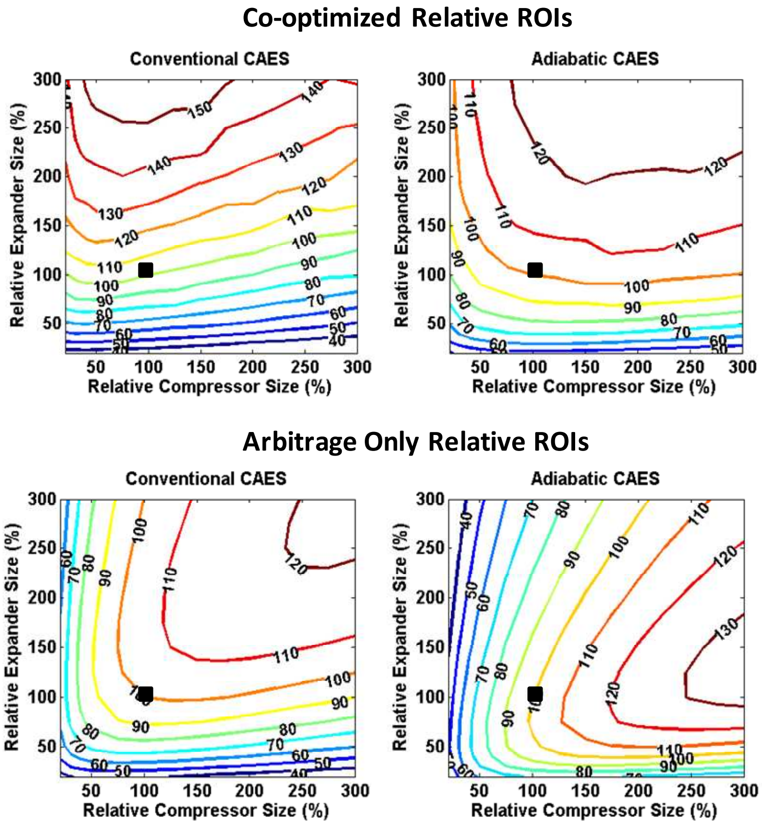

Figure 13. Contour plots showing the relationship between relative returns on investment (ROIs) and expander and compressor sizes, based on CAES performance in the reference region in NYISO in 2007. The black squares show a 100%:100% expander to compressor relationship.

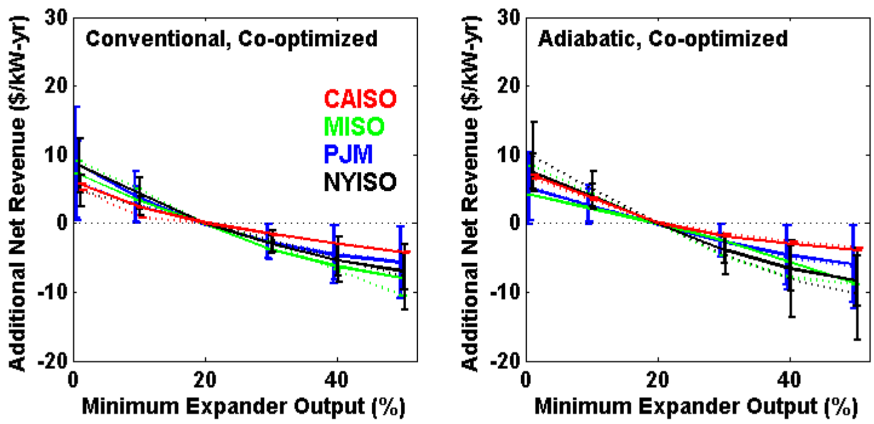

Figure 14. Additional net revenue as a function of minimum expander output. The sensitivity for each region in shown by color, the reference locations are shown by solid lines, and the high value locations are shown by dashed lines.

Table Captions:

Table 1. Historical market data used in this analysis

Table 2. Operating parameters for several CAES technologies

Table 3. NYISO market parameters and CAES Net Revenues

Table 4. Cost breakdown for a conventional CAES system deployed with a salt cavern

Table 5. Fraction of optimal CAES net revenue captured using a one day back-casting dispatch

Tables:

Table 1. Historical market data used in this analysis

Market	Years with data	Reference Location	High Value Location
California Independent System Operator (**CAISO**)[1]	**2009 -2010**	Kern County, CA (Pacific Gas & Electric CAES Plant)[2]	Anaheim, CA
MidWest Independent System Operator (**MISO**)[3]	**2009**	Dallas County, IA (Iowa Stored Energy Park [4])	Upper Michigan
New York Independent System Operator (**NYISO**)[5]	**2002-2009**	Watkins Glenn, NY (NYSEG CAES Plant[6])	Long Island, NY
PJM[7]	**2005-2009**	Norton, OH (Norton CAES plant[8])	New Jersey (PSEG)

[1]CAISO switched from a real-time zonal market to a day-ahead nodal market in April 2009. We use market data starting in June 2009 through May 2010 to avoid potential price volatility from the first two months of operating the day-ahead nodal market. http://oasis.caiso.com.

[2] H. LaFlash "Compressed Air Energy Storage" Pacific Gas and Electric Company, Nov 3, 2010. http://www.sandia.gov/ess/docs/pr_conferences/2010/laflash_pge.pdf

[3] www.midwestmarket.org

[4] http://www.isepa.com/

[5]www.nyiso.com. NYSIO updated their day-ahead market dispatch algorithm in 2005, which generally increased the value of storage dispatched to day-ahead prices.

[6] U.S. Salt Corp's Watkins Glen facility

[7]www.pjm.com. The PJM acronym historically represented Pennsylvania, New Jersey and Maryland, but the PJM market has now extended beyond these state boundaries.

[8] http://www.firstenergycorp.com/NewsReleases/2009-11-23%20Norton%20Project.pdf

Table 2. Operating parameters for several CAES technologies

	Conventional CAES[1,2,3]		**Adiabatic/Isothermal CAES**[2,3,4,5]	
	Range in Literature	Reference Case / [Sensitivity Range]	Range in Literature	Reference Case / [Sensitivity Range]
Heat Rate (kJ/kWh)	4,185 - 4,220[2], 4,430[1]	4,220 / [3,700 – 5,250]	-	-
Energy Ratio (kWh-in/kWh-out)	0.72[1,2]	0.72 / [0.65 – 0.90]	-	-
Roundtrip Efficiency (kWh-out/kWh-in)	-	-	0.50[5], 0.72[3,4], 0.77[2,4]	0.72 / [0.60 – 0.90]
Minimum Expander and Compressor Capacity (Minimum/Maximum Capacity)	Application dependent	0.20 / [0.01 – 0.50]	Application dependent	0.20 / [0.01 – 0.50]
Ratio of Expander to Compressor Size (Expander Size:Compressor Size)	Application Dependent 3:1[5], 1.5:1[6], 1.35:1[7]	1:1 / [0.1:1 – 3:1; 1:0.1 – 1:3]	Application dependent 1:1.33[2]	1:1 / [0.1:1 – 3:1; 1:0.1 – 1:3]
Electrical Energy Storage (hours)[a]	Application dependent	20 / [5 – 40]	Application dependent	20 / [5 – 40]

[1] [16]
[2] [14]
[3] [15]
[4] General Compression, www.generalcompression.com, accessed May 2010.
[5]Huntorff, Germany
[6]Norton Stored Energy Plant
[7]McIntosh CAES plant

Table 3. NYISO market parameters and CAES Net Revenues

	Reference Zone (Central)			High Value Zone (Long Island)		
	2007	2008	2009	2007	2008	2009
Mean Electricity Price ($/MWh)	61	68	36	158	178	83
Natural Gas Price ($/GJ)[1]	7.8	10.0	5.1	7.8	10.0	5.1
Arbitrage Only Net Revenue ($/kW-yr)	37	25	12	124	118	62
Co-Optimized Net Revenue ($/kW-yr)	58	51	33	145	159	84
Additional Net Revenue from Co-Optimized Dispatch ($/kW-yr)	21	26	21	21	41	22

[1]Natural gas markets in the United States typically use price units of $/mmBTU, and the price conversion to GJ was calculated based on 1 mmBTU = 1.055 GJ.

Table 4. Cost breakdown for a conventional CAES system deployed with a salt cavern[1]

	Conventional CAES[2]		**Adiabatic CAES[3]**	
	Cost ($2009/kW)	**Cost Fraction (%)**	**Cost ($2009/kW)**	**Cost Fraction (%)**
Compressor	84	11	129	13
Heat Exchanger	33	4	150	15
High pressure expander	60	8	114	11
Low pressure expander	140	19	100	10
Electrical and Controls	44	6	60	6
Cavern Development	75	10	86	8
Construction materials and labor	215	29	255	25
Indirect Costs	98	13	137	13
Total	749	-	1031	-

[1]Based on [14]. Costs were modified from 2007 U.S. dollars to 2009 U.S. dollars using a consumer price index calculator.
[2]These costs represent a conventional CAES system with 10 hours of storage and an oversized expander (110 MW) relative to the compressor (81MW). Capital costs are expressed in terms of expander capacity.
[3]These costs represent an adiabatic CAES system with 10 hours of storage and an oversized compressor (96 MW) relative to the expander (72MW). Capital costs are expressed in terms of expander capacity.

Table 5. Fraction of optimal CAES net revenue captured using a one day back-casting dispatch

		Conventional CAES		**Adiabatic CAES**	
		Arbitrage Only	Co-optimized	Arbitrage Only	Co-optimized
NYISO	Reference	63%	79%	65%	80%
	High Value	84%	85%	70%	78%
PJM	Reference	65%	73%	74%	81%
	High Value	78%	84%	76%	85%