Economics of electric energy storage for energy arbitrage and regulation in New York

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Abstract

Unlike markets for storable commodities, electricity markets depend on the real-time balance of supply and demand. Although much of the present-day grid operates effectively without storage, cost-effective ways of storing electrical energy can help make the grid more efficient and reliable. We investigate the economics of two emerging electric energy storage (EES) technologies: sodium sulfur batteries and flywheel energy storage systems in New York state's electricity market. The analysis indicates that there is a strong economic case for EES installations in the New York City region for applications such as energy arbitrage, and that significant opportunities exist throughout New York state for regulation services. Benefits from deferral of system upgrades may be important in the decision to deploy EES. Market barriers currently make it difficult for energy-limited EES such as flywheels to receive revenue for voltage regulation. Charging efficiency is more important to the economics of EES in a competitive electricity market than has generally been recognized.

Keywords: electric energy storage; electricity markets; restructuring

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1. Introduction

Electric energy storage is the capability of storing electricity or energy to produce electricity and releasing it for use during other periods when the use or cost is more beneficial. Representative technologies include redox flow batteries (Bartolozzi, 1989; Price, 2000), sodium sulfur batteries (Oshima et al., 2005), lead acid batteries (EPRI, 2003), flywheels (Lazarewicz, 2005), pumped hydroelectric storage, and compressed air energy storage (CAES). Battery and flywheel technologies are geographically less constrained than hydroelectric storage or CAES. Here we analyze the economics of such installations in an operating energy market administered by the New York Independent Systems Operator (NYISO).

An electric energy storage (EES) unit can participate in electricity markets in a number of ways, depending on its energy storage and delivery characteristics (Schoenung et al., 1996). Despite numerous advances in EES technologies (Gyuk et al., 2005) and technical benefits offered (EPRI, 2003), markets have not yet adopted EES applications other than pumped hydro on a large scale. At present there are several non-hydro energy storage technologies at varying stages of maturity available at the utility scale.

Initial economic studies of EES systems focused on applications for peak shaving and as a capacity resource (Sobieski and Bhavaraju, 1985). In recent years there has been increased attention on evaluating the economics of EES systems as backup for intermittent renewable sources. Some examples include wind and CAES (DeCarolis and Keith, 2006), wind and hydro or batteries (Bathurst, 2003), solar photovoltaic and batteries (Su et al., 2001; Fabjan et al., 2001). Since the emergence of competitive electric energy markets, several studies of the economics of EES systems have appeared, including a ranking of potential opportunities (Butler et al., 2003), life cycle costs for batteries, CAES, and flywheels (Schoenung and Hassenzahl, 2003), a general calculation of potential revenues in California and PJM without regard to technologies (Eyer et al., 2004), pumped hydroelectric storage using PJM market data (Perekhodtsev, 2004) and comparison of energy arbitrage revenues (from storing power purchased at off-peak times and selling it on-peak) in North American and European energy markets (Figueiredo et al., 2005).

We have evaluated the economics of two emerging EES technologies, Sodium Sulfur (NaS) batteries for energy arbitrage and flywheel energy storage systems for regulation services in New York state’s electricity market. New York was chosen because market data is readily available and an initial survey indicated that both energy arbitrage and regulation services might be profitable there. We considered several factors in selecting technologies for market analysis. First, very large scale storage such as pumped hydro and CAES continue to have potential where geographic considerations allow their use. In New York most suitable pumped hydro sites have already been developed. Most prospective CAES sites are in western New York, where the economic case for energy storage is the weakest (Walawalkar et al., 2005) as we discuss below. Second, lead-acid batteries were not included in this analysis because utilities are reluctant to accept this technology for electric market applications due to relatively short service life, significant environmental effects and high maintenance costs (EPRI, 2003). Third, the extremely high cycle life of flywheel devices make them viable solutions for applications such as frequency regulation. Ultracapacitors and superconducting magnetic energy storage (SMES) devices, which also have excellent cycle life, may have potential in these applications, but are not yet mature enough to consider in a utility application.

Here we present results for NaS batteries and flywheels. A detailed analysis was also performed for zinc bromide batteries and vanadium redox batteries. The results for zinc bromide and vanadium redox batteries are not shown here because these technologies are less economically favorable than NaS or flywheels. With the currently available data, NaS batteries have the best economics among the battery technologies for MW size utility applications (EPRI, 2006).

2. Energy Storage Technologies

Sodium-sulfur batteries are based on a high-temperature electrochemical reaction between sodium and sulfur, separated by a beta alumina ceramic electrolyte. Sodium-sulfur batteries have excellent cycle life and are relatively mature products, with over 55 installations worldwide for peak shaving and load leveling applications at the distribution level; two installations are in the United States (EPRI, 2003).

Flywheels store energy in the angular momentum of a spinning mass. During charge, the flywheel is spun up by a motor with the input of electrical energy; during discharge, the same motor acts as a generator, producing electricity from the rotational energy of the flywheel. Most flywheel designs are capable of several hundred thousand full charge-discharge cycles (Lazarewicz, 2005). The energy sizing of a flywheel system is dependent on the size and speed of the rotor and the power rating is dependent on the motor-generator. The disadvantages of flywheels are relatively poor energy density and large standby losses. Beacon Power Corporation is currently testing flywheels for frequency regulation applications at the transmission level in New York and California (Gyuk et al., 2005; Lazarewicz, 2005). The EES technologies considered in this work are described in detail in EPRI (2003, 2004) and Gyuk et al. (2005).

Table 1 summarizes the EES technical parameters and costs for NaS batteries and flywheels. The base estimates were derived from the data available in EPRI (2003) and updated based on information from manufacturers. The capital cost and annual operations and maintenance cost estimates have a relatively large range, as these technologies are yet to be widely commercialized, and no published data are available. For NaS batteries the cycle life (5,000 – 20,000 cycles) is sensitive to operational parameters such as depth of discharge and environmental factors, whereas for the flywheel the cycle life (100,000 – 2,000,000 cycles) is based on design specifications. The service life estimate was derived based on the cycle life and expected usage for various market applications.

3. NYISO Markets and EES

The New York Independent System Operator (NYISO) administers the wholesale energy markets in New York. NYISO's electricity markets include installed capacity, energy and ancillary services. Approximately 45% of New York electricity is transacted in the NYISO day-ahead market, 5% is transacted in the NYISO real time market and half through bilateral contracts (NYISO, 2005a).

We have aggregated the eleven zones defined by NYISO (Fig. 1) into three (Table 2). These regions are distinct in terms of geography and in energy price distribution. There is a clear similarity in the on-peak and off-peak prices in the zones in each region. This pattern is observed in all three periods used for this analysis: complete year, summer capabilities period and winter capabilities period. Zonal price distributions are given in Appendix A.

Table 3 lists the distribution of the mean location-based marginal pricing (LBMP) prices for different zones and seasons for 2001-04 period. Correlation analysis of the zonal LBMP prices was performed to test the validity of the grouping of the eleven zones into our three regions. All zones in the NY West region have a correlation coefficient higher than 0.98, and all zones in the

NY East region have a correlation coefficient higher than 0.96. New York City and Long Island have a lower correlation coefficient, 0.82, but these zones exhibit a much greater degree of correlation with each other than with the other zones. In addition, the analysis of mean as well as 5th and 95th percentile values of LBMP data for 2001-04 justifies grouping these zones in single region (Appendix A).

4. The analytic framework: market scenario analysis

NYISO has recognized in its market design special resources that have limited electric energy output/reduction capability for short time periods and/or require a recharge period (NYISO, 2005a). These energy-limited resources (ELRs, which are generally peaking plants or demand side resources) must demonstrate the ability to deliver energy for a minimum of 4 consecutive hours each day. Thus, NaS batteries can be utilized as ELRs (for energy arbitrage), whereas flywheels cannot. The latter are particularly well suited for providing regulation service due to the very high cycle life.

Net revenues for each market can be calculated as follows. Energy arbitrage net revenue is the difference between revenue received from energy sale (discharge) during ‘N’ on-peak hours and the charging cost for off-peak energy which includes a factor ($1/\eta$) for additional energy required due to losses. Let T_{DS} denote the starting hour of discharge, T_{CS} the starting hour of the charging period, $P_{Energy}(t)$ the LBMP price of energy for the corresponding hour and $Q_{Energy}(t)$ the amount of energy delivered during the hour. Then

$$\sum R_{Energy}(t) = \sum_{t=T_{DS}}^{T_{DS+N(energy)}} [P_{Energy}(t) * Q_{Energy}(t)] - \frac{1}{\eta} \sum_{T_{CS}}^{T_{CS+N(energy)}} [P_{Energy}(t) * Q_{Energy}(t)] \qquad (1)$$

Regulation and frequency response service revenues are calculated based on the market clearing price for the regulation service. EES are paid for both charging and discharging when responding to appropriate regulation signals from the ISO.

$$\sum R_{regulation}(t) = \sum_{t=T_{DS}}^{T_{DS+N(regulation)}} P_{regulation}(t) * |Q_{regulation}(t)| \qquad (2)$$

Appendix B lists the binding constraints for these equations. A global optimization for optimal operation of EES providing a combination of energy and ancillary services would require data such as distribution of hours for operating reserve pickups (the actual delivery of energy by units selected for providing operating reserves) and detailed technical data to analyze impact of changing operational parameters on capital cost, which are not yet available. In the next section we examine the economics of EES under different scenarios by comparing the net revenues that can be generated from a 1 MW EES for different applications.

5. Energy Arbitrage Revenues

We have analyzed the energy arbitrage potential of energy-limited resources for energy delivery times of 10 hours, 4 hours and 2 hours. These periods of energy arbitrage were selected based on two criteria. First, EES technologies considered for long duration energy arbitrage have efficiencies between 65% and 85% (the ratio of input power to output power is ~ 1.2 – 1.4). Assuming that these units are charged and discharged at the same rate, this results in 20-40% additional charging time, limiting the maximum duration for energy sale to 10 hours. Second, NYISO allows EES participating under the energy-limited resources program to receive capacity credits if they can provide energy for 4 successive hours (NYISO, 2005a). Thus for an application with energy arbitrage as the only service, 4 hours energy discharge capability was considered as the minimum duration necessary for market participation in energy-only markets.

NYISO market energy data from 2001-04 were used to determine the statistical net revenue potential for 3 different operating conditions (2 hour, 4 hour, and 10 hour). The 2 hour net revenue was calculated in anticipation of mixed mode operations involving both energy and regulation. For determining the net revenues, the maximum potential revenue period and minimum potential cost period for each day in the three regions were determined.

The maximum electricity price period has a relatively wide distribution and shows a seasonal shift in the maximum revenue period. The maximum revenue period for 4 hour energy arbitrage is from 12 PM to 4 PM in the summer period, and shifts to 3 PM to 7 PM in the winter period. This information was used in calculating the anticipated revenues by using the LBMP for corresponding hours. Under the base scenario it was assumed that a market participant will bid in the EES resources based on the seasonal forecast for peak hours based on historical data. With use of better forecasting tools utilizing weather data, load forecasts and historical prices, market participants may be able to increase revenue by capturing on-peak and least cost periods on a weekly or even daily basis.

Fig. 2 shows the potential cumulative net revenues for different durations of energy arbitrage in the New York City region during the 2001-04 period. The total net revenue was determined by using a 1 MW size energy storage unit for 10 hour, 4 hour, and 2 hour energy arbitrage. The base case efficiency was assumed to be 83% (a ratio of input energy to output energy of 1.2). For this efficiency, 10 hour energy arbitrage would have generated approximately $250,000 of revenue during the 2001-04 period in New York City. The energy arbitrage revenues for 4 hour and 2 hour sales would have been approximately $170,000 and $100,000 respectively.

Fig. 3 shows the cumulative probability distribution of daily net revenues that would have been received during 2001-2004 by EES for energy arbitrage for 2 hour, 4 hour, and 10 hour periods. Although the marginal net revenue from operating the unit for shorter durations (2 or 4 hours) is significantly higher than operating the unit for 10 hours, the operator receives more total daily revenue when the units are run for a longer duration. There is a 50% probability that the EES will receive over $50/MW-day in net revenues for 2 hour energy arbitrage. This net revenue increases to over $105/MW-day for 4 hour and $ 140/MW-day for 10 hour operations.

If the power rating of EES and the rate of discharge are not limiting factors, then an EES with a 10 MWh energy capacity could theoretically be operated at higher power levels for shorter periods of time. A unit might be used for energy arbitrage delivering 1 MW for 10 hours, 2.5 MW for 4 hours, or 5 MW for 2 hours. In practice, operations would be limited by the unit’s power rating and the power conversion system. A more detailed analysis involving capital cost estimates is required to determine if it is more economical to deploy EES units that are able to provide 2-4 hour energy requirement at higher power levels.

6. Impact of Round Trip Efficiency

The net revenue from energy arbitrage is highly sensitive to EES efficiency, because inefficient systems are forced to buy some on-peak power. Fig. 4-a shows the expected net revenues from energy arbitrage for 2001-2004 in the New York City region from a 1 MW EES, as a function of efficiency. In New York City, an EES with round trip efficiency of less than 73% would earn more net revenues for 4 hour energy arbitrage than for 10 hours. An EES unit with efficiency of less than 67% would earn more net revenues from 2 hour energy arbitrage than 10 hour energy arbitrage. Lower round trip efficiency means that the EES must be charged for longer, increasing charging costs and reducing the price differential between on-peak and off-peak operation. Due to the different energy prices in the three regions the switchover points between these operating modes occur at slightly different efficiencies for the various geographic regions. Fig. 4-b shows a similar graph for the NY West region.

7. Installed Capacity Market (ICAP)

ICAP revenues are a way to encourage new generation capacity additions in areas with tight supply reserve margins. An EES in NYISO capable of providing 4 hours or more of capacity can generate ICAP revenues in addition to the revenues received from energy or ancillary markets. Table 4 shows the summary results for the ICAP monthly market auctions for 2004-2005. There are also locational requirements for New York City (zone J) and Long Island (zone K) that require load-serving entities serving these areas to procure a certain percentage (80% and 99% respectively) of the regional peak load from resources within the individual zones. (NYISO, 2005a) Due to this locational requirement, the ICAP revenues for NYC region are significantly higher than rest of the state and contribute significantly towards making EES operations economical in this region.

8. Regulation Revenue

EES can be used for providing various required ancillary services:1) regulation services required to track moment-to-moment fluctuations in load and supply and 2) reserve services for meeting intra- and inter-hour changes in the supply and load curves (NYISO, 2005b).

Regulation and frequency response services assist in maintaining the system frequency at 60 Hz and allows compliance with reliability criteria set by NERC, the New York State Reliability Council (NYSRC), and the Northeast Power Coordinating Council (NPCC). Resources providing regulation service are directed to move from each real time dispatch base point (usually every 5 minutes) in 6 second intervals at their stated ramp rate (Hirst, 2001). Resources can participate in the regulation market if they have automatic generation control capability within the New York control area. Some EES technologies, particularly flywheel systems, can be used to offer regulation services. Flywheels cannot be utilized for energy applications due to their short duration (15 minute) energy storage capacity. For pumped hydro facilities, Perekhodtsev (2004) has shown that frequency regulation can offer one of the highest value markets for storage. In NYISO, our work shows that regulation offers the maximum revenue potential amongst all the ancillary services, followed by spinning, non-spinning and 30 minute operating reserves (Walawalkar et al., 2005).

9. EES Economics

Table 5 summarizes the expected net revenue for energy arbitrage and regulation in all three regions. The maximum-case scenario represents the data from a year (2005) with maximum net revenues, whereas the minimum-case scenario represents the year with minimum net revenues (2002). The estimates for average net revenues were calculated using the average revenue and cost figures from 2001-2005 data[1].

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[1] Although the initial study was based on 2001-2004 data, for the final economic analysis we included market data from 2005. The year 2005 was unique in that the NYISO's software for the real time market (SMD 2) was substantially revised. In addition the export fees to ISO-NE were eliminated and the summer was considerably warmer than it had been in the previous years of NYISO operation. Finally, fuel costs towards the end of summer increased drastically. All of these factors resulted in changed market economics in 2005.

New York City has the highest revenue potential for energy arbitrage of the three regions in New York State. In NY East and NY West, regulation services have the maximum revenue potential and lowest uncertainty (regulation prices have less variance than energy prices). However, there is some regulatory uncertainty in utilizing flywheels for regulation services. Flywheels have much smaller regulation capacity per installation, and rely on the changing sign of the regulation control signal, so that the unit can be continuously charged and discharged (i.e. an average zero net energy regulation signal). Currently flywheel manufacturers and NYISO officials are trying to develop ways to determine an appropriate evaluation criterion for calculating the performance of flywheels for regulation services (the original evaluation criteria were devised for large central generators providing regulation services by use of automated generation controls).

10. Additional Benefits

Since most current installations of EES are based on the valuation of the benefits offered by EES for either power reliability or system upgrade cost deferral, we have roughly quantified these benefits based on a review of the literature. The benefits accrue to different market participants. For example, deferral of system upgrade costs are important to utilities or LSEs, whereas commercial and industrial customers will value the power quality and reliability benefit (Butler et al., 2003; EPRI, 2003; Eyer et al. 2004). As the focus of current paper is on supply side applications of EES, we limit the discussion of these additional benefits to the system upgrade cost deferral.

System upgrade cost deferral. Properly located EES can allow utilities to defer transmission and distribution upgrade costs. Such suitable locations can be characterized by infrequent maximum load days with peak load occurring only during a few hours in a day; slow load growth indicates that for a few years EES can be used to defer T&D upgrade and high transmission access charges that can be avoided with distributed resources. These benefits could range from $150,000 - $1,000,000/MW-year (EPRI, 2003; Eyer et al., 2004).

11. Net present value analysis

Based on the range of annual net revenue estimates for 2001-2005, and the EES cost data, the net present value (NPV) was calculated for various EES technologies in different regions to evaluate the economics of these technologies. The discount rate used was 10% and the project life considered was 10 years. To be conservative, we used $150,000/MW-year as the average value for the system upgrade deferral benefits of EES to augment the revenues that can be realized by a typical market participant in New York.

We have performed a sensitivity analysis, finding that the most important factors influencing the economics of EES are revenue, charging cost, capital costs and round trip efficiency. Fig. 5 shows the results of the sensitivity analysis, using a NaS installation in NYC with the average scenario as the base case. The base case had a NPV of $258,000. Each bar indicates the variability in the NPV as a result of changing an individual factor. For example, the NPV will increase from $11,500 to $750,000 if the capital cost of the EES installation is reduced from $1.8 million to $ 1 million, keeping all other inputs at base level. Based on the results of the sensitivity analysis, we performed Monte Carlo simulations which used NYISO market data to study the impact of capital cost and efficiency on the distribution of NPV.

Fig. 6 shows the NPV distribution for a NaS installation in all 3 regions using the average cost estimates for capital and O&M costs for NaS installation. This simulation was performed for

500 iterations using a triangular distribution for the revenue and charging cost from 10 hr energy arbitrage in all 3 regions. For each set of simulations we kept the capital cost and efficiency constant: once an EES unit is selected, these parameters are fixed and cannot change. For comparing the impact of different estimates of capital cost and efficiency we ran the simulations by selecting 3 different values (lower bound, average and upper bound) for capital cost as well as efficiency. For triangular distributions of net revenue, the minimum, maximum and average values for net revenue were selected for each region based on the data presented in Table 5. From Fig. 6, it can be seen that the only region with positive mean NPV is New York City, where the operating revenues are significantly higher than other regions due to higher capacity credits and energy prices. The mean NPV for a NaS installation in New York City is approximately +\$190,000, whereas a similar unit in NY East and NY West will have mean NPVs of -\$475,000 and -\$560,000 respectively. Another way of stating these results is that there is 66% probability that the NaS installation in New York City would have a positive NPV, whereas a similar unit in NY East and NY West has only 7% and 2% probability of having a positive NPV. The major factor contributing to the uncertainty (and to the long tails in the cumulative distribution functions) of the project's NPV is the variation in energy revenues and charging costs from the actual market data.

Fig. 7 compares the distribution of NPV from using flywheels for regulation to that from using NaS batteries for energy arbitrage. The comparison is based on the anticipated 24 hour regulation revenues in the NY East region for flywheels and 10 hour energy arbitrage using NaS batteries in the New York City area. Energy arbitrage has a larger uncertainty than regulation services. The mean NPV from utilizing flywheels for regulation is considerably higher (\$454K) than utilizing an NaS battery for 10 hour energy arbitrage (\$189K).

12. Conclusion

EES technologies capable of discharging at higher power and energy densities than conventional lead-acid batteries can offer benefits to various market participants in competitive electricity markets. There are technical as well as market barriers for the wide-scale integration of electric energy storage for wholesale market applications. At present, most energy storage technologies have higher capital costs than peaking power alternatives such as gas turbines (flywheels are similar in capital cost to a combined-cycle natural gas turbine, and NaS batteries are 1.8 to 3.5 times the capital cost of an NGCC unit). While capital costs are falling somewhat due to technology improvements, significant manufacturing economies of scale have not yet been realized (EPRI, 2003; 2004).

Based on market data from 2001-2005, we find that NaS and flywheel units in the New York City region have a high probability of positive NPV for both energy arbitrage and regulation. Significant opportunities exist in the NY East and NY West regions for regulation. Load-serving entities may be able to capture benefits from system upgrade deferral which may pay for the unit in approximately 4 years of operation.

EES units which require an average zero net energy regulation signal are sometimes denied participation in regulation markets. PJM and the California ISO have initiated efforts to evaluate the performance of flywheels for regulation services. The results of these studies may allow such devices to be widely deployed. Current market rules also do not permit most EES technologies to participate in 10 minute synchronous spinning reserve markets, which can offer roughly 15% of the revenue available from regulation (Walawalkar et al., 2005).

A recent analysis (Butler et al., 2003) argued that EES systems with low round trip efficiency and low equipment cost would be quite viable for energy arbitrage. In contrast, our research indicates that achieving lower costs by sacrificing efficiency can have a significantly adverse effect on the economics of the project. Thus while designing and developing EES systems for electricity market participation, it is crucial to maintain or increase efficiency while reducing the capital cost.

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Appendix A Regional Distribution Of Energy Prices

Tables A-1 through A-6 summarize the statistical analysis of zonal LBMP prices for 11 NYISO zones for the complete year, the summer capabilities period and winter capabilities period based on 2001-04 data.

For NYISO's operations, the on-peak period is defined as the hours between 7am and 11pm inclusive, prevailing Eastern Time, Monday through Friday, except for North American Electric Reliability Council (NERC) defined holidays. The off-peak period is defined as the hours between 11pm and 7am, prevailing Eastern Time, Monday through Friday, and all day Saturday and Sunday, and NERC defined holidays. NYISO has defined the summer capability period as May 1 through October 31 and the winter capability period as November 1 through April 30.

Appendix B Constraints

The binding constraints for the revenues from various energy markets can be expressed as

1. $\mathrm{N_{Energy}} * \mathrm{Q_{Energy}} \le \eta * \mathrm{N_{Max}} * \mathrm{Q_{Max}}$

i.e. total energy delivered is less than or equal to product of round trip efficiency and the rated maximum energy capacity of the EES;

2. $0.6 \le \eta \le 0.9$

i.e. round trip efficiency of the EES devices considered are in the range of 0.6 to 0.9;

3. $0 \le \mathrm{N_{Energy}} \le \mathrm{N_{Max}} \le {}^{24*\eta}\!/\!_{(1+\eta)}$ or $0 \le \mathrm{N_{DSR}} \le \mathrm{N_{Max}} \le {}^{24*\eta}\!/\!_{(1+\eta)}$

Maximum duration for Energy Arbitrage or DSR participation is limited by the lower of rated maximum discharge duration or 24*η/ (1+η), where η is the efficiency of EES. E.g. maximum duration for an EES with efficiency of 1 would be 24/2 = 12 hours, i.e. 12 hours to charge and 12 hours discharge;

4. $0 \le N_{regulation} \le 24 - \left(\dfrac{\eta+1}{\eta} \right) * N_{Energy}$

Maximum duration for providing regulation is calculated by subtracting the no of hours required for energy arbitrage (both charge and discharge) from 24 hours. For flywheel since regulation is the only service provided, it can be utilized for all 24 hours; and

5. $0 \le \left(N_{Spinning}\ Or\ N_{NonSpin}\ Or\ N_{30\min Operating} \right) \le N_{Max} \le \left(24 - \dfrac{\eta+1}{\eta} \left(N_{Energy} \right) - N_{regulation} \right)$

Similarly a market participant can utilize the remaining capacity of the EES for providing remaining ancillary services depending on the technical capability and market rules.

Table 1: Summary of technical and cost details for sodium sulfur batteries and flywheels.

	NaS Battery	**Flywheel**
EES Size	1 MW (10 MWh)	1 MW (0.25 MWh)
Total Capital Cost	$1,150,000 -2,250,000	$550,000 -750,000
Annual O&M Cost	$15,000 – 90,000	$20,000 - $30,000
Cycle Life	5,000 – 20,000	100,000 – 2,000,000
Service Life (years)	12 – 20	15 – 25

Table 2: NYISO zones and regions used in this analysis

Region	Zones
NY West	• West (A) • Genesee (B) • Central (C) • North (D) • Mohawk (MH) Valley (E)
NY East	• Capital (F) • Hudson Valley (G) • Millwood (H) • Dunwoodie (I)
New York City	• NYC (J) • Long Island (K)

Table 3. NYISO Location Based Marginal Price Distribution Across Zones for 2001-2004.

		Peak ($/MWh)			Off-peak ($/MWh)		
Region	**Zone**	**All year**	**Summer**	**Winter**	**All Year**	**Summer**	**Winter**
NY West	**West**	$45.40	$45.31	$45.49	$32.45	$30.98	$33.94
	Genesee	$47.46	$46.98	$47.95	$33.91	$32.27	$35.58
	Central	$48.36	$47.93	$48.79	$34.65	$33.02	$36.31
	North	$48.07	$47.22	$48.94	$35.23	$33.41	$37.08
	MH Valley	$49.72	$49.16	$50.29	$35.87	$34.17	$37.60
NY East	**Capital**	$54.09	$54.11	$54.07	$38.44	$36.91	$40.01
	Hudson Valley	$55.23	$55.96	$54.50	$38.60	$37.26	$39.97
	Millwood	$55.32	$56.26	$54.38	$38.34	$37.06	$39.65
	Dunwoodie	$56.13	$57.09	$55.15	$38.84	$37.60	$40.09
New York City	**NYC**	$66.43	$67.22	$65.64	$44.12	$43.99	$44.25
	Long Island	$65.77	$66.83	$64.69	$46.47	$46.50	$46.44

Table 4: ICAP Revenues 2004-2005 (Monthly Auctions). Market data from Patton (2005).

	Minimum Market Clearing Price ($/kW-Month)	Maximum Market Clearing Price ($/kW-Month)
New York City	$ 6.96	$ 11.86
Long Island	$ 3.25	$ 9.50
Rest of State	$ 0.25	$ 1.70

Table 5. Summary of Potential Annual Net Revenues for various Applications by Region. Min is the minimum revenue year (2002), Avg is the average of 2001-2005, and Max is the maximum revenue year (2005).

Application	**Expected Net Revenue (Thousand $/MW-year)**		
	New York City ***Min – Avg - Max***	***NY East*** ***Min – Avg - Max***	***NY West*** ***Min – Avg - Max***
Energy Arbitrage 10 Hours	$87 - $180 - $240	$41 - $58 - $84	$29 - $46 - $66
Energy Arbitrage 4 Hours	$76 - $162 - $211	$33 - $50 - $73	$25 - $42 - $62
Regulation 24 Hours	$163 - $203 - $248	$163 - $203 - $248	$197 - $203 - $211

Table A-1. Regional Distribution of On-Peak LBMP Prices ($/MWh) for 2001-2004.

Region	Zone	5th Ptcl	Mean	95th Pctl
New York City	Long Island	$32.62	$65.77	$109.18
New York City	NYC	$32.33	$66.43	$109.39
NY East	Hudson Valley	$30.11	$55.23	$88.73
NY East	Capital	$28.62	$54.09	$85.98
NY East	Dunwoodie	$30.14	$56.13	$90.84
NY East	Millwood	$29.82	$55.32	$89.62
NY West	Genesee	$23.07	$47.46	$75.40
NY West	North	$23.44	$48.07	$76.99
NY West	MH Valley	$24.29	$49.72	$79.18
NY West	Central	$23.79	$48.36	$76.35

Table A-2. Regional Distribution of On-Peak LBMP Prices ($/MWh) for Summer Capabilities Period 2001-2004.

Region	Zone	5th Ptcl	Mean	95th Pctl
New York City	Long Island	$36.30	$66.83	$104.75
New York City	NYC	$37.82	$67.22	$104.55
NY East	Hudson Valley	$33.74	$55.96	$86.13
NY East	Capital	$32.03	$54.11	$78.01
NY East	Dunwoodie	$34.06	$57.09	$89.79
NY East	Millwood	$33.60	$56.26	$88.67
NY West	Genesee	$26.00	$46.98	$68.13
NY West	North	$25.97	$47.22	$67.80
NY West	MH Valley	$27.20	$49.16	$70.53
NY West	Central	$27.00	$47.93	$69.17
NY West	West	$25.60	$45.31	$65.86

Table A-3. Regional Distribution of On-Peak LBMP Prices ($/MWh) for Winter Capabilities Period 2001-2004.

Region	**Zone**	**5th Ptcl**	**Mean**	**95th Pctl**
New York City	Long Island	$30.99	$64.69	$112.65
New York City	NYC	$29.91	$65.64	$114.68
NY East	Hudson Valley	$27.68	$54.50	$90.12
NY East	Capital	$25.77	$54.07	$90.18
NY East	Dunwoodie	$27.62	$55.15	$91.40
NY East	Millwood	$27.41	$54.38	$90.42
NY West	Genesee	$22.26	$47.95	$80.67
NY West	North	$22.80	$48.94	$82.82
NY West	MH Valley	$23.63	$50.29	$84.83
NY West	Central	$22.98	$48.79	$81.42
NY West	West	$21.76	$45.49	$76.67

Table A-4. Regional Distribution of Off-Peak LBMP Prices ($/MWh) 2001-2004.

Region	Zone	5th Ptcl	Mean	95th Pctl
New York City	Long Island	$23.35	$46.47	$77.67
New York City	NYC	$20.57	$44.12	$73.85
NY East	Hudson Valley	$19.81	$38.60	$63.18
NY East	Capital	$19.52	$38.44	$62.81
NY East	Dunwoodie	$19.66	$38.84	$64.38
NY East	Millwood	$19.49	$38.34	$63.45
NY West	Genesee	$17.65	$33.91	$56.01
NY West	North	$18.01	$35.23	$57.63
NY West	MH Valley	$18.32	$35.87	$59.02
NY West	Central	$17.96	$34.65	$56.92
NY West	West	$17.40	$32.45	$53.11

Table A-5. Regional Distribution of Off-Peak LBMP Prices ($/MWh) for Summer Capabilities Period 2001-2004.

Region	**Zone**	**5th Ptcl**	**Mean**	**95th Pctl**
New York City	Long Island	$23.18	$46.50	$74.31
New York City	NYC	$20.82	$43.99	$70.25
NY East	Hudson Valley	$19.48	$37.26	$59.45
NY East	Capital	$19.28	$36.91	$58.73
NY East	Dunwoodie	$19.02	$37.60	$61.07
NY East	Millwood	$18.88	$37.06	$59.99
NY West	Genesee	$16.58	$32.27	$50.76
NY West	North	$16.16	$33.41	$51.99
NY West	MH Valley	$16.81	$34.17	$53.70
NY West	Central	$17.11	$33.02	$51.85
NY West	West	$16.46	$30.98	$48.07

Table A-6. Regional Distribution of Off-Peak LBMP Prices ($/MWh) for Winter Capabilities Period 2001-2004.

Region	Zone	5th Ptcl	Mean	95th Pctl
New York City	Long Island	$23.53	$46.44	$80.78
New York City	NYC	$20.43	$44.25	$78.73
NY East	Hudson Valley	$19.98	$39.97	$68.05
NY East	Capital	$19.67	$40.01	$68.05
NY East	Dunwoodie	$19.94	$40.09	$69.00
NY East	Millwood	$19.81	$39.65	$68.08
NY West	Genesee	$18.12	$35.58	$61.57
NY West	North	$18.75	$37.08	$63.34
NY West	MH Valley	$18.94	$37.60	$64.65
NY West	Central	$18.40	$36.31	$62.34
NY West	West	$17.84	$33.94	$58.16

Fig. 1. The eleven NYISO market zones grouped into 3 regions. Based on the NYISO LBMP Map © NYISO, used with permission. The 3 regions, NYC, NY East and NY West show a clear similarity in on-peak and off-peak prices in zones within each region.

Fig. 2. Cumulative net revenue (2001-2004) from energy arbitrage in New York City. The cumulative net revenue for year 2001-2004 from energy arbitrage was determined by using a 1 MW sized EES unit with 83% round trip efficiency for 10 hour, 4 hour and 2 hour energy arbitrage, using NYISO market price data from the four years.

Fig. 3. Cumulative probability distribution of daily net revenues for energy arbitrage in New York City. The cumulative probability distribution of daily net revenues ($/MW-Day) was obtained by using a 1MW sized EES unit with 83% round trip efficiency for energy arbitrage during 2001-04 for 10 hour, 4 hour and 2 hour energy arbitrage.

Fig. 4-a. Cumulative net revenues as a function of EES efficiency in the New York City region. The net revenue from energy arbitrage is highly sensitive to the round trip efficiency of the EES. Round trip efficiency can be used to determine the energy rating of the EES and the maximum duration of energy arbitrage that can operated economically.

Fig. 4-b. Cumulative net revenues as a function of EES efficiency in the New York West region.

Fig. 5. Sensitivity Analysis for the net present value (NPV) of NAS installation for 10 hour energy arbitrage across NYISO regions.

Fig. 6. Cumulative probability distribution of NPV for NAS installation for 10 hour energy arbitrage across NYISO regions. The distribution reflects to market prices over the years studied.

Fig. 7. Comparison of distribution of NPV for a flywheel used for 24 hour regulation and an NAS battery used for 10 hour energy arbitrage in New York City.

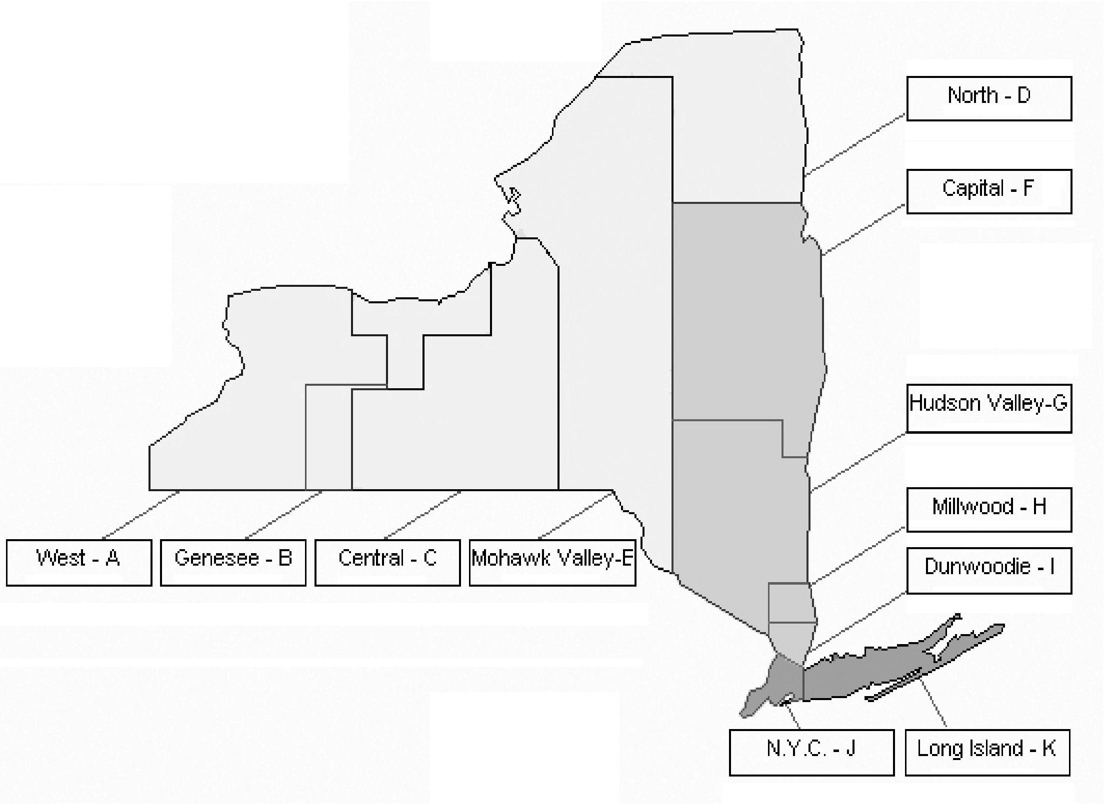
North - D
Capital - F
Hudson Valley-G
Millwood - H
Dunwoodie - I
West - A
Genesee - B
Central - C
Mohawk Valley-E
N.Y.C. - J
Long Island - K

Fig. 1

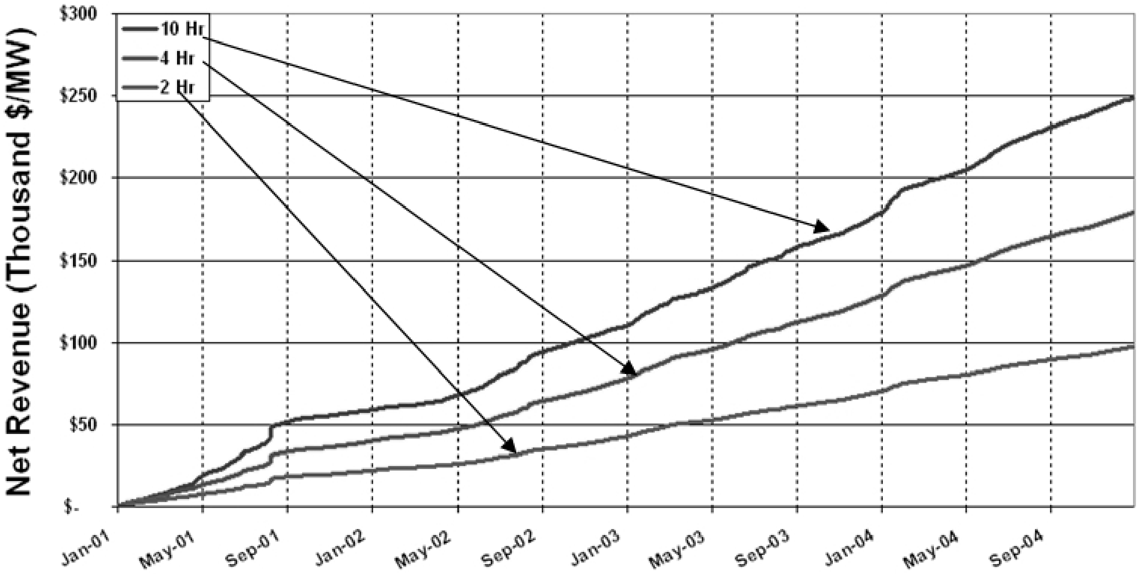
Net Revenue (Thousand $/MW)
$300
$250
$200
$150
$100
$50
$-
10 Hr
4 Hr
2 Hr
Jan-01
May-01
Sep-01
Jan-02
May-02
Sep-02
Jan-03
May-03
Sep-03
Jan-04
May-04
Sep-04

Fig. 2

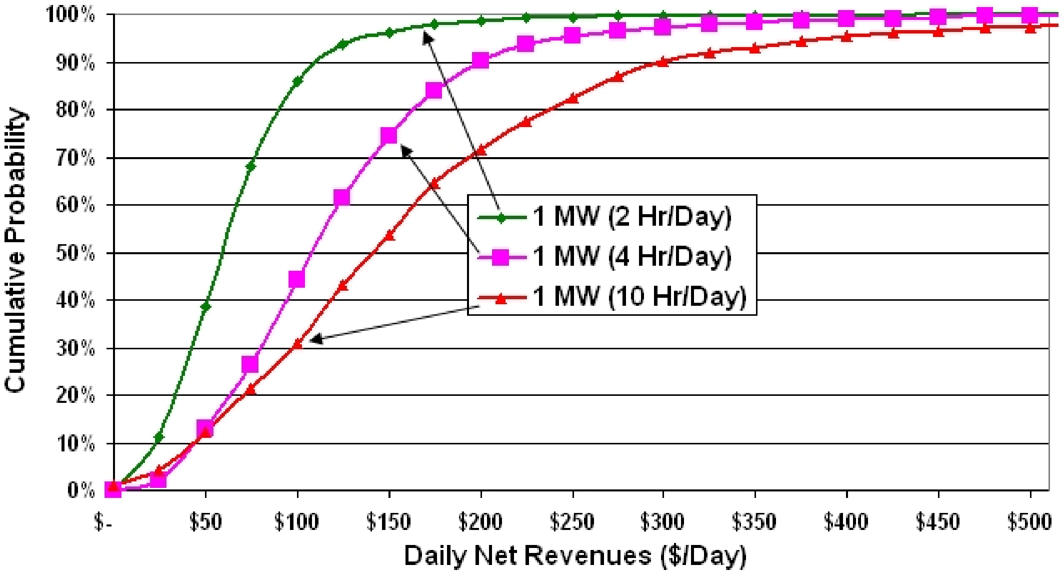
Cumulative Probability
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
$-
$50
$100
$150
$200
$250
$300
$350
$400
$450
$500
Daily Net Revenues ($/Day)
1 MW (2 Hr/Day)
1 MW (4 Hr/Day)
1 MW (10 Hr/Day)

Fig. 3

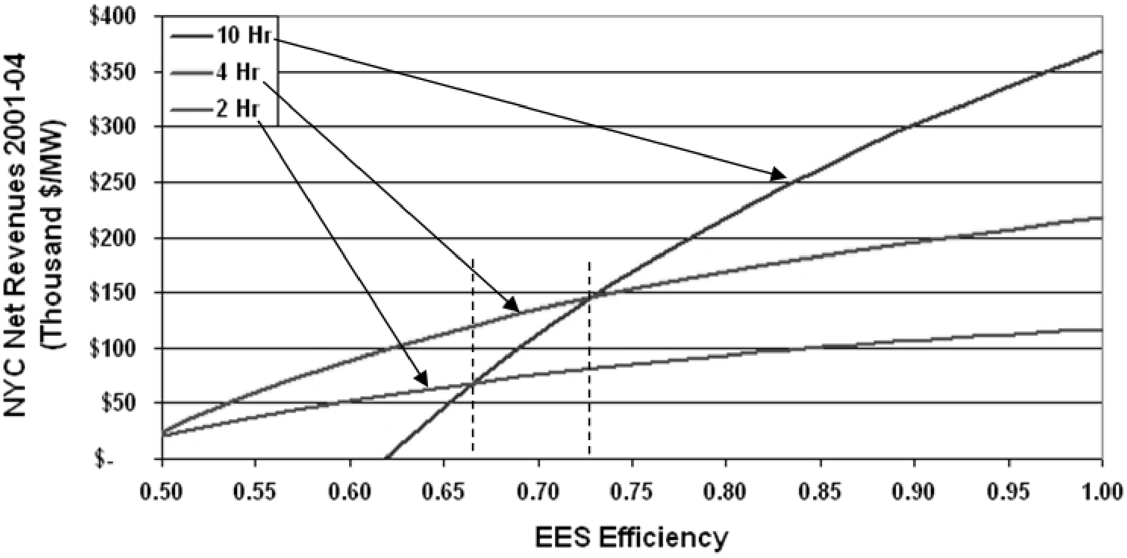
10 Hr
4 Hr
2 Hr
NYC Net Revenues 2001-04 (Thousand $/MW)
$400
$350
$300
$250
$200
$150
$100
$50
$-
0.50
0.55
0.60
0.65
0.70
0.75
0.80
0.85
0.90
0.95
1.00
EES Efficiency

Fig. 4-a

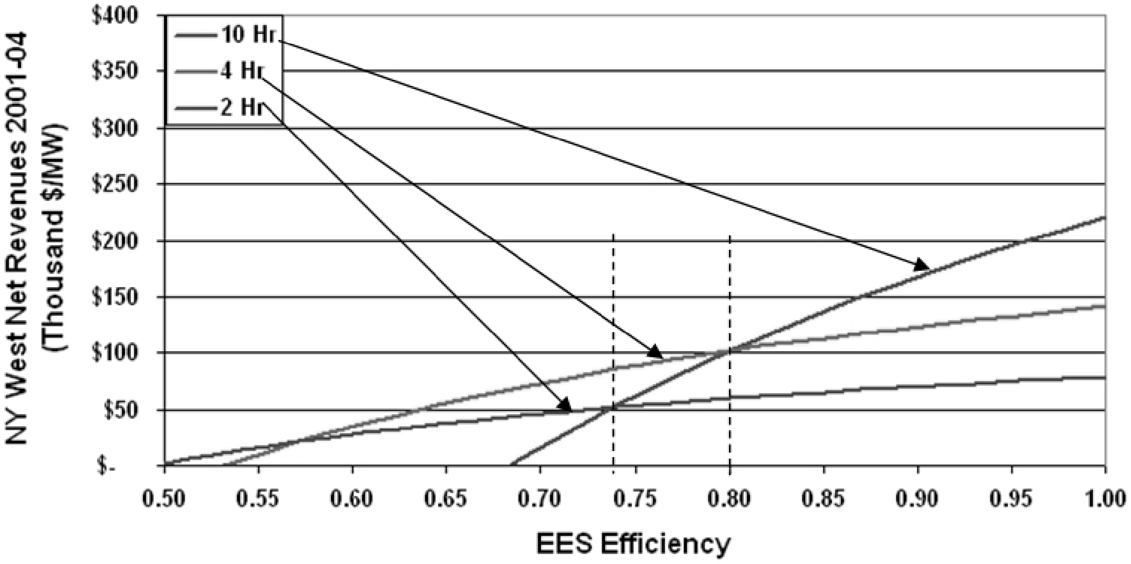
10 Hr
4 Hr
2 Hr
NY West Net Revenues 2001-04 (Thousand $/MW)
$400
$350
$300
$250
$200
$150
$100
$50
$-
0.50
0.55
0.60
0.65
0.70
0.75
0.80
0.85
0.90
0.95
1.00
EES Efficiency

Fig. 4-b

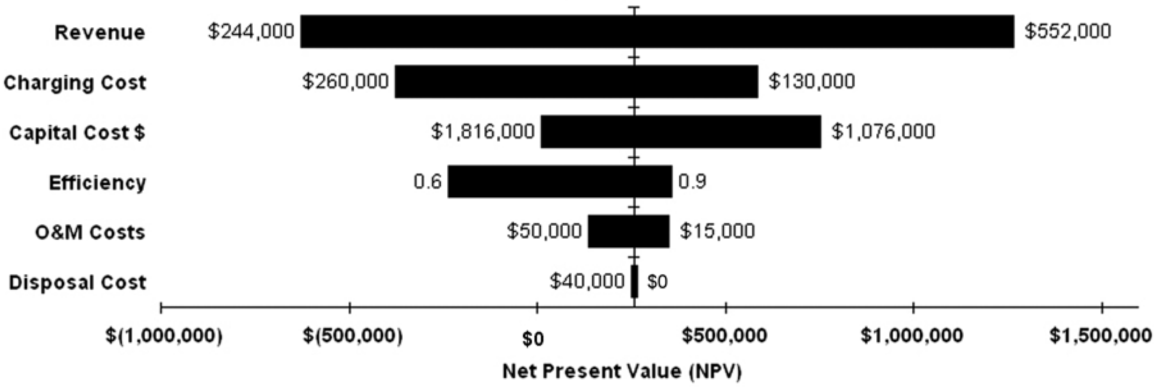
Revenue
$244,000
$552,000
Charging Cost
$260,000
$130,000
Capital Cost $
$1,816,000
$1,076,000
Efficiency
0.6
0.9
O&M Costs
$50,000
$15,000
Disposal Cost
$40,000
$0
$(1,000,000)
$(500,000)
$0
$500,000
$1,000,000
$1,500,000
Net Present Value (NPV)

Fig. 5

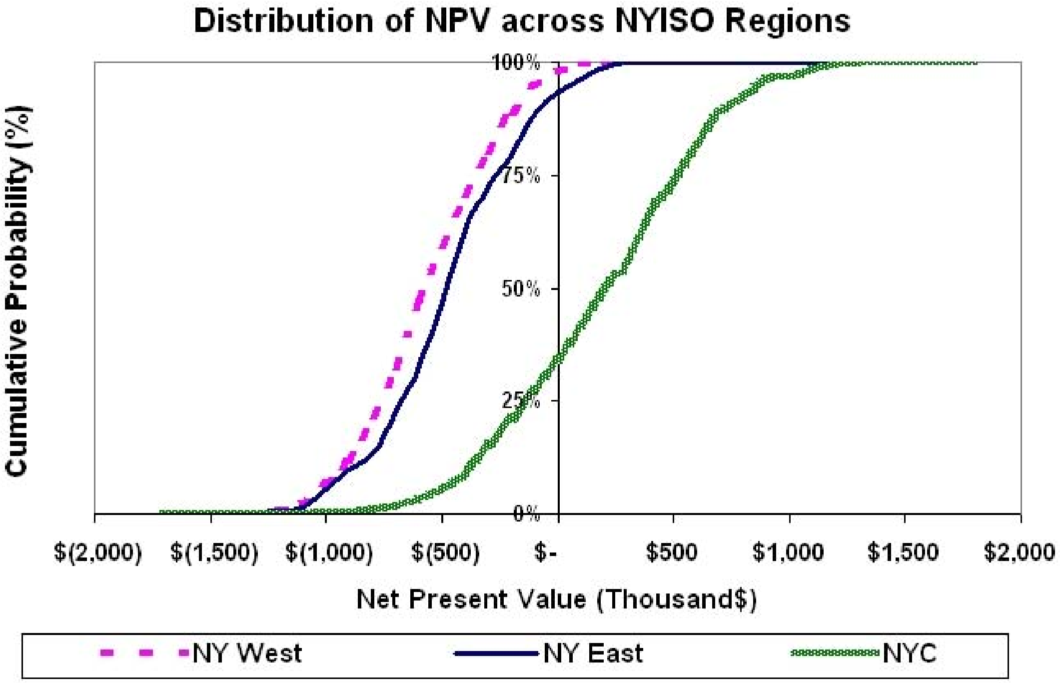
Distribution of NPV across NYISO Regions
Cumulative Probability (%)
100%
75%
50%
25%
0%
$(2,000)
$(1,500)
$(1,000)
$(500)
$-
$500
$1,000
$1,500
$2,000
Net Present Value (Thousand$)
NY West
NY East
NYC

Fig. 6

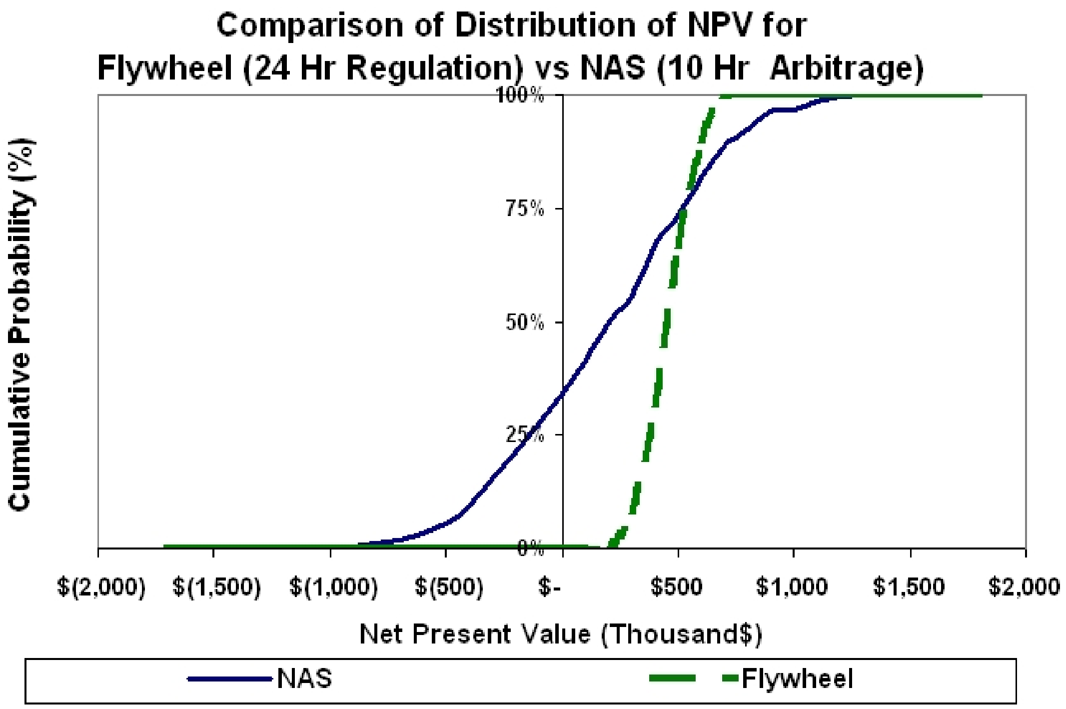
Comparison of Distribution of NPV for
Flywheel (24 Hr Regulation) vs NAS (10 Hr Arbitrage)
Cumulative Probability (%)
100%
75%
50%
25%
0%
$(2,000)
$(1,500)
$(1,000)
$(500)
$-
$500
$1,000
$1,500
$2,000
Net Present Value (Thousand$)
NAS
Flywheel

Fig. 7