# MINI-COMPRESSED AIR ENERGY STORAGE FOR TRANSMISSION CONGESTION RELIEF AND WIND SHAPING APPLICATIONS

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NEW YORK STATE
ENERGY RESEARCH AND
DEVELOPMENT AUTHORITY

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Final Report

Prepared for the

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# Abstract

Compressed air energy storage (CAES) is a moderately effective technology for bulk storage applications and an effective technology for stabilizing electrical grids at utility scale. This project investigated the feasibility of adapting a high-pressure natural gas storage technology based on manifolded pressure vessels for storing compressed air and combining it with ~10MW low-cost CAES energy conversion equipment to provide a geologically independent energy storage option for locations throughout New York State.

The design is optimized around general capabilities so that a package can be assembled from existing components with minimal adaptation.

We examined potential value from the following sources:

1. Intrinsic arbitrage of value from off-peak hours to on-peak hours [and extrinsic trading value]
2. Advantages in location, comparing co-location with wind generation and in urban sites
3. Capacity value
4. Ability to defer construction of transmission and (mainly) distribution construction
5. System support value

The project found that for mini-CAES facilities the value is restricted to intrinsic arbitrage of value from off-peak hours to peak hours and possibly some limited capacity value. This value is not adequate to justify the cost of the design.

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# SUMMARY

Compressed air energy storage (CAES) is a cost-effective technology for bulk storage applications at utility scale. In a CAES plant, electrical energy is stored in the form of high-pressure air. A compressor driven by an electric motor/generator compresses air with off-peak power, and stores it in a suitable underground geologic structure such as a salt cavern. When the CAES plant generates power, the compressed air is released from the cavern, heated in a recuperator before mixing and combusting with fuel, and expanded through a turbine to generate electricity.

This project investigated the feasibility of adapting a high-pressure natural gas storage technology based on manifolded pressure vessels for storing compressed air and combining it with small-scale, low-cost CAES energy conversion equipment to provide a geologically independent energy storage option for locations throughout New York State.

The system design planned a package that can be assembled from existing components with minimal adaptation. Conceptually, a package that has flexible design characteristics could be applied in various locations without customizing each package.

**Findings:**

The project found that the sources of value from a mini-CAES facility are markedly different than the sources of value from a large (135 MW or greater) facility. The mini-CAES units are better suited to urban locations where it is not feasible to implement large-scale CAES projects.

1. Mini-CAES units are more valuable when co-located with the load than with wind generation.
2. Mini-CAES units can obtain a small contribution toward their costs from the spread between off-peak energy costs and on-peak delivery value.
3. Mini-CAES units could provide some value by deferment of transmission and distribution expenditures, however; in most instances, utilities may not support this form of value and even if recognized, it is likely to be limited.
4. Mini-CAES units appear ready to provide long-term value in the improvement of power quality and reliability; however, utilities benefit more by obtaining such value from larger power facilities. No commercial or industrial-scale applications that would benefit were identified.

The major finding is that the value delivered by mini-CAES will not support the cost of a mini-CAES project. Some possible enhancements to cost, energy ratio, and value delivered are identified, but the possible improvements are foreseen to be too limited to bridge the value gap.

# 1 INTRODUCTION

Compressed air energy storage (CAES) is a cost-effective technology for bulk storage applications at utility scale. In a CAES plant, electrical energy is stored in the form of high-pressure air. A compressor driven by an electric motor/generator compresses air with off-peak power and stores it in a suitable underground geologic structure such as a salt cavern. When the CAES plant generates power, the compressed air is released from the cavern, heated in a recuperator before mixing and combusting with fuel, and expanded through a turbine to generate electricity.

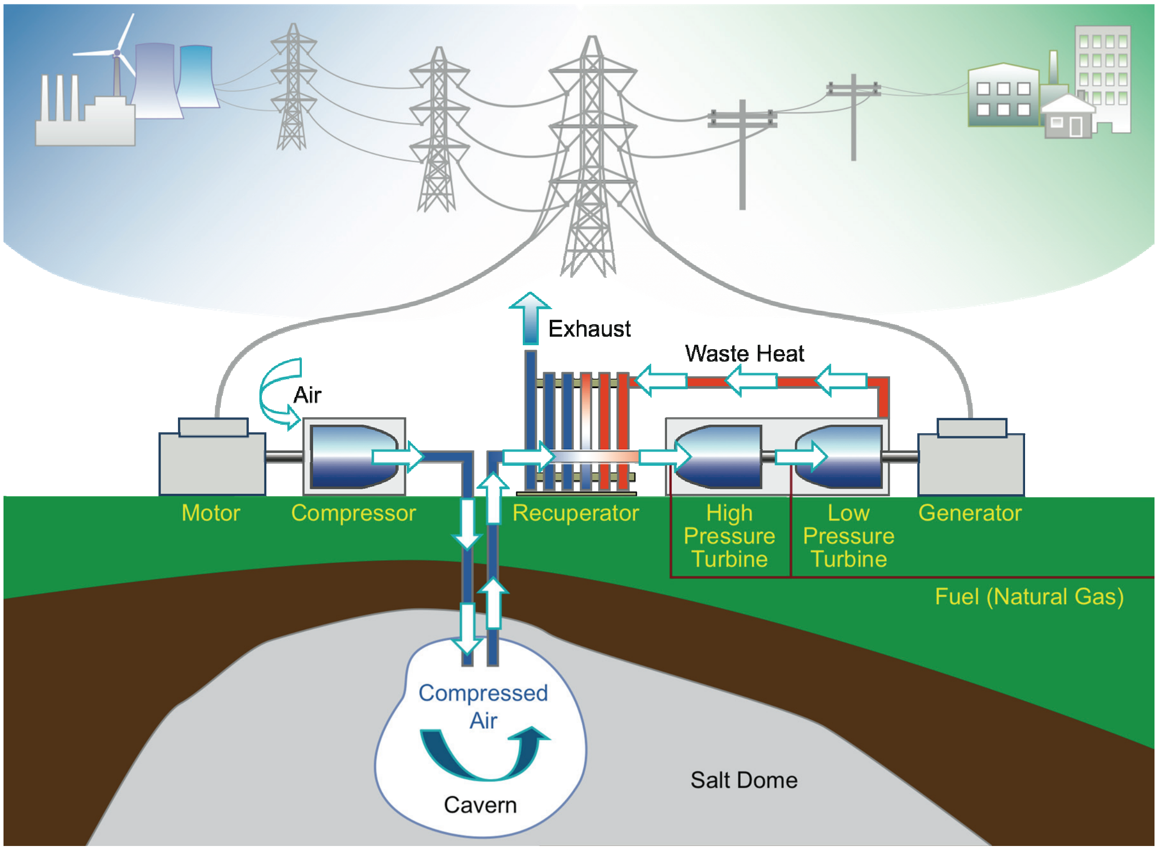
This project investigated the feasibility of adapting a high-pressure natural gas storage technology based on manifolded pressure vessels for storing compressed air and combining it with small-scale, low-cost CAES energy conversion equipment to provide a geologically independent energy storage option for locations throughout New York State. This ~12MW “mini-CAES” concept could be suitably sited to enhance the value of unpredictable renewable energy sources such as wind power generation.

The system design is optimized around general capabilities so that a package can be assembled from existing components with minimal adaptation. Since the unit is relatively small, for CAES, the plan was to develop a package that has flexible design characteristics that could be applied in various locations without customizing each package.

## 1.1 How CAES Works

A CAES plant stores electrical energy in the form of air pressure, and then recovers this energy as an input for future power generation. Essentially, the CAES cycle is a variation of a standard gas turbine generation cycle. In the typical simple cycle gas-fired generation cycle, the turbine is physically connected to an air compressor. Therefore, when gas is combusted in the turbine, approximately two-thirds of the turbine’s energy goes back into air compression. With a CAES plant, the compression cycle is separated from the combustion and generation cycle. Off-peak or excess electricity is used to “pre-compress” air, which is held for storage in an underground cavern, typically a salt cavern. When the CAES plant regenerates the power, the compressed air is released from the cavern and heated through a recuperator before being mixed with fuel (natural gas) and expanded through a turbine to generate electricity. Because the turbine’s output no longer needs to be used to drive an air compressor, the turbine can generate almost three times as much electricity as the same size turbine in a simple cycle configuration, using far less fuel per MWh produced. The stored compressed air takes the place of gas that would otherwise have been burned in the generation cycle and used for compression power. Figure 1 – “How CAES Works” illustrates this system.

Figure 1: How CAES Works[1]



The volume of air storage required for a typical CAES plant is most economically provided by geological structures. Salt caverns, aquifers, depleted oil and gas reservoirs, and rock mines have all been considered as possibilities for air storage in a CAES application. However, this study considered the viability of mini-CAES facilities, which require a much more limited amount of storage than CAES plants of traditional scale. In addition, if the concept is to be viable it needs to be flexibly located.

For these reasons the design presented eschewed geological storage and used a form of compressed air storage designed by EnerSea Transport LLC: VOLANDS$^{TM}$ Gas Storage. This method uses banks of high strength steel piping in vertical configurations to achieve the desired result. Although the storage units would be in a 10 to 12 story building if built at ground level, they would most likely be placed in an excavation, resulting in a four to six story building. This provides flexible storage quantities at a constant pressure and temperature without the conventional geological constraints. Figure 2 – “VOLANDS$^{TM}$ Gas Storage” illustrates this concept.

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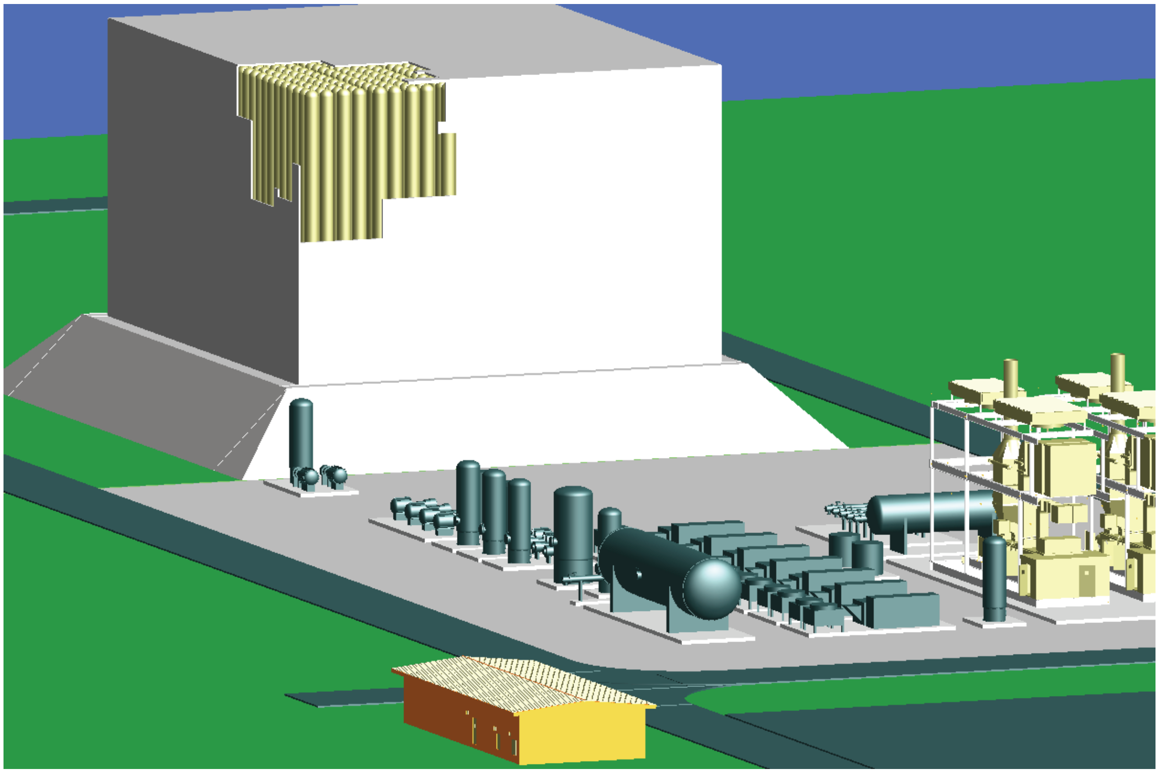
[1] The Economic Impact of CAES on Wind in TX, OK, and NM, Final Report, June 27, 2005, prepared for the “Texas State Energy Conservation Office”, p14© Ridge Energy Storage & Grid Services

Figure 2: VOLANDS™ Gas Storage[2]



## 1.2 Value of CAES in Service

The value that CAES facilities provide is estimated by considering a series of values that are provided in different ways. The total of these separate values provides the complete answer. At a large scale facility, the value may be attributed to:

- Store power in the production region for delivery during a period when the transmission system is not constrained
- Conversely, store power in a consuming area during hours when transmission to the consuming area is not constrained, for use during peak periods
- Store intermittent power for delivery as block power
- Deliver power in accordance with dispatch, avoiding penalties
- Provide any or all of the above services in situations with wind generation

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[2] Courtesy of EnerSea Transport LLC, which is affiliated with Ridge Energy Storage and Grid Services, L.P.

- Absorb power during off-peak periods, shadow ramp up, or shadow ramp down to reduce changes in dispatch of “base load” units, which cause added maintenance
- Provide significant system reserves
- Deliver VAR support, black start, and related ancillary services
- Provide the aforementioned services in a location for a period of time to defer investment in transmission and/or distribution system upgrades

Because CAES systems are highly flexible in dispatch, the operational costs for intermittent operation are limited. Since the unit uses compressed air, there is no capacity derating of the turbine due to elevation or summer operating temperatures. Permitting issues are similar to a small, low-emissions generation plant, which is often less significant than permitting a transmission line.

The value of a large-scale CAES system is often misunderstood. Because it is common to fill the CAES plant off-peak and to sell on-peak, it is sometimes assumed that the key value is found in this “peak to base” spread income. Previous[3] interviews with the plant manager at the sole operating CAES plant in the United States, located in McIntosh[4], AL, (“McIntosh”) and with storage capable hydro, suggest that they are being operated primarily to continue operation of coal and other boiler plants during off hours, and to provide blocks of continuous operations for other types of fossil plants, both of which provides relief of maintenance costs associated with cycling of “base load” generation units. While that sometimes corresponds to a peak to base cycle, it reportedly affects operations within “peak” and within “base” periods. It has also been estimated that deferring transmission upgrades may have a significant positive impact.[5]

### 1.3 Value of Mini-CAES in Service

Upon examination of the value streams and the power system results, it was apparent that mini-CAES facilities are more applicable to sites near the consuming load. While certain specific applications in the wind generation regions can benefit from 50 to 150 MWh of energy storage with ~12MW discharge capability, in general, larger bulk requirements prevail at those locations.

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[3] Interviews conducted in prior years on unrelated projects with operators of multiple hydro projects and with the plant manager at McIntosh.

[4] McIntosh is a town located in Washington County, Alabama, 44 miles north of Mobile. The Alabama Electric Cooperative’s ~110 MW compressed air energy storage plant, operating since 1991, is located near this town and is conventionally referred to as “McIntosh.”

[5] “DOE Storage Systems Annual Peer Review Program, Annual Peer Review”, November 10-11, 2004, Washington, DC, Bob Haug, Executive Director, Iowa Association of Municipal Utilities.

Since mini-CAES is a form of distributed generation (and storage), it is more amenable to parts of that value chain, which the study initially assumed might include:

- Spread energy value (buy low cost power and generate during peak value hours)
- Dispatch benefits (matching retail strategies and in particular renewable retail strategies to appropriate generation in the more economical day ahead markets)
- Deferral of distribution expansions, together with improving utilization of existing facilities
- Reduction of outages (grid stability)
- Capacity generation
- Reduction of losses

# 2 METHODOLOGY

The study performed some iterations of the following steps in order to develop a view of the test design:

- Value the power on the New York Grid
- Analyze the storage and production hours
- Design the power and compression system
- Estimate the measurable value from spread energy service
- Estimate the possible value from other forms of service

After this initial iteration, we settled on the design cycle of five hours of storage and nine hours of production as the base scenario. We then focused design efforts on this scenario and ultimately calculated the economic scenarios.

Once the design matured, an economic analysis was developed to evaluate the opportunity.

## 2.1 Methodology for Determining Compression and Generation Hours

The analysis of the grid system was performed in two parts. First, an analysis of power values on the grid was performed using the GE Energy Consulting Multi Area Production Simulation (MAPS) energy production software program database. The MAPS assumptions built upon work performed for the NYSERDA Contract 6218, “The Effects of Integrating Wind Power on Transmission System Planning, Reliability, and Operations”. GE included the MAPS database developed by the New York State Public Service Commission and the wind profiles developed by AWS Truewind in this analysis.

As a second stage, we developed a model to take hourly model outputs from GE MAPS and rank the hourly prices to estimate how a mini-CAES plant would operate as a stand-alone resource responding to electricity pricing, including recognition of its actions as a hybrid source with wind. The GE MAPS system did not include the mini-CAES facility, as it was immaterial to the market analysis due to the limited size of the compression and generation.

The analysis of the compression and generation possibilities began by taking the GE MAPS’ resulting values for the test year in a separate Excel model that was developed for the project to create an understanding of the most likely energy storage periods and the most likely energy delivery periods. Energy storage and delivery periods were each observed for three key characteristics:

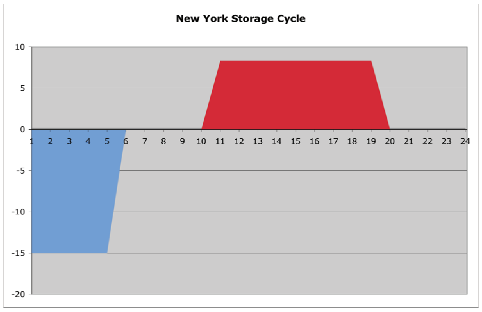
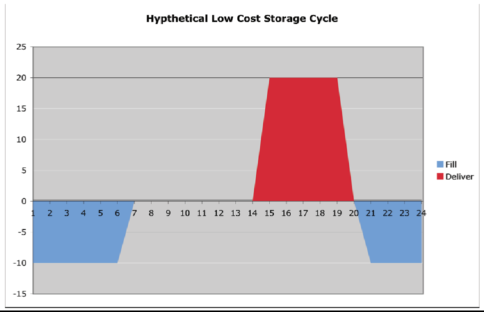
- Frequency of occurrence
- Duration of occurrence
- Value during occurrence

The analysis was used to compare ratios of storage hours to energy generation hours of 1:1, 1:2, and 2:1. After this step, we estimated that the greatest value was probable for a storage interval of about five hours and a delivery interval of about twice that period. After considering design options for the range of available equipment selections, as they would perform when modified for CAES service, we settled on a base scenario with five hours of compression and nine hours of generation. Although the initial analysis focused on the hourly compression of air and production of power to develop equipment design criteria, we ran economic scenarios (discussed later) that also included consideration of sales of capacity and that supported the bias toward larger storage amounts, and also the ratio of compression to generation duration.

The estimate of cycle requirements had a major impact on the design decisions. The turbine generator was chosen for its clear suitability and the convenient availability of information. The other components were then scaled to match this starting point. First, the storage was sized for quantity of air required for the nine hour generation period, and then the compression was matched to deliver the required storage value within the constraint of the five-hour energy storage period. Variations to the design were tested to consider ways to optimize the thermodynamic cycle, as described separately below in “Mini-CAES Specifications and Equipment Selection”.

Conceptually, the compression and storage periods, while varying in time each day, are roughly as shown in the following “Figure 3 – System Value” on the left. This quick compression, long production cycle is less than optimal if a mini-CAES project is to provide a solution. On the right, in order to illustrate the unfavorable characteristics of the design cycle, we display a non-existent example of the system characteristics that would favor a mini-CAES installation: long periods of low cost compression opportunity and short periods of high value generation. For a given size of mini-CAES generation module, this theoretical situation would lower the compression and storage capital cost.

Figure 3: System Value

<table>
<tr><td>Observed New York Value Pattern</td><td>Hypothetical mini-CAES Favorable Pattern</td></tr>
<tr><td>
</td><td>
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</table>

## 2.2 Key Issues

Initially, effort was focused upon three parts of the system:

- estimate of the appropriate hours for compression and expansion
- design of the rotating equipment
- identifying potential sources of value

It became apparent that a fourth area required attention; namely the design of a low cost repeatable system. Because only about 35% of the cost estimate was applied to the equipment, it is necessary to consider the possibility that costs could be reduced by as much as 50% through a determined effort to find a repeatable commercial design that would require the minimum effort for engineering and construction.

The project tested a “what if” scenario to consider the fourth value component. The capital cost estimates for the engineered package are analyzed to consider the lower bound of feasible costs for this configuration. In this way we could test whether a significant but potentially possible facility cost improvement should be investigated by future projects.

## 2.3 Economic Analysis

The Contractor prepared simple return on capital comparisons for the mini-CAES facility to determine return on investment potential. No assumptions were included for development costs or financing costs, beyond the cost of capital. This subtask determined the economic feasibility of the proposed mini-CAES plant design.

# 3 SYSTEM MODELING OF POWER PRICES

## 3.1 Background

NYSERDA previously funded a project to “Study the Effects of Integrating Wind Power on Transmission System Planning, Reliability and Operation." The project resulted in a database of wind energy and profiles for wind generation projects covering New York State. This data includes the database developed by the NY Public Service Commission and the wind profiles developed by AWS Truewind. In order to use the data for the mini-CAES project, this database was updated to reflect current price projections for 2008 (the year of analysis) as well as projections of new capacity additions.

Understanding the dynamics of the local wind regime and power system is necessary for determining what type of mini-CAES plant would best suit the market needs in New York State. One potential value of the storage facility is the reduction or elimination of the imbalance penalties that can result from wind generation. Historically, penalties have been charged if the delivered energy has varied by more than 3% from the schedule set in the day ahead market. These penalties could range up to $100/MWh for under production and zero payments for any energy produced in excess of the schedule. These penalties were deemed necessary to prevent the generators from “gaming” the market and withholding resources that had been promised in the day ahead market, thereby driving up prices for the remaining generation. However, because of imperfect forecasting capabilities the wind may over or under produce compared to its schedule. Recent rulings from the Federal Energy Regulatory Commission (FERC) have broadened this range to +/-10% and have limited the penalties to 10% of the hourly spot price value, but it would still not be uncommon for the actual wind generation to be outside of this range. Roughly coincidentally with the beginning of the study, it was proposed that the wind projects would have a more relaxed requirement that would largely eliminate the penalties, therefore the project calculations assume that the facility would pay no penalty.

The production cost modeling of the New York control area was performed with the General Electric Company Multi Area Production Simulation Program (MAPS) to determine hourly marginal cost profiles for multiple locations throughout the state for scenarios both with and without wind generation. In general, the MAPS Program simulates the “day ahead” operation of the New York Independent System Operator (NYISO) through which 90% to 95% of the system energy clears. By modeling the load and wind uncertainty, the model estimates the impact on the real time prices in order to determine the value that the CAES may provide due to its rapid response capabilities.

## 3.2 MAPS Overview

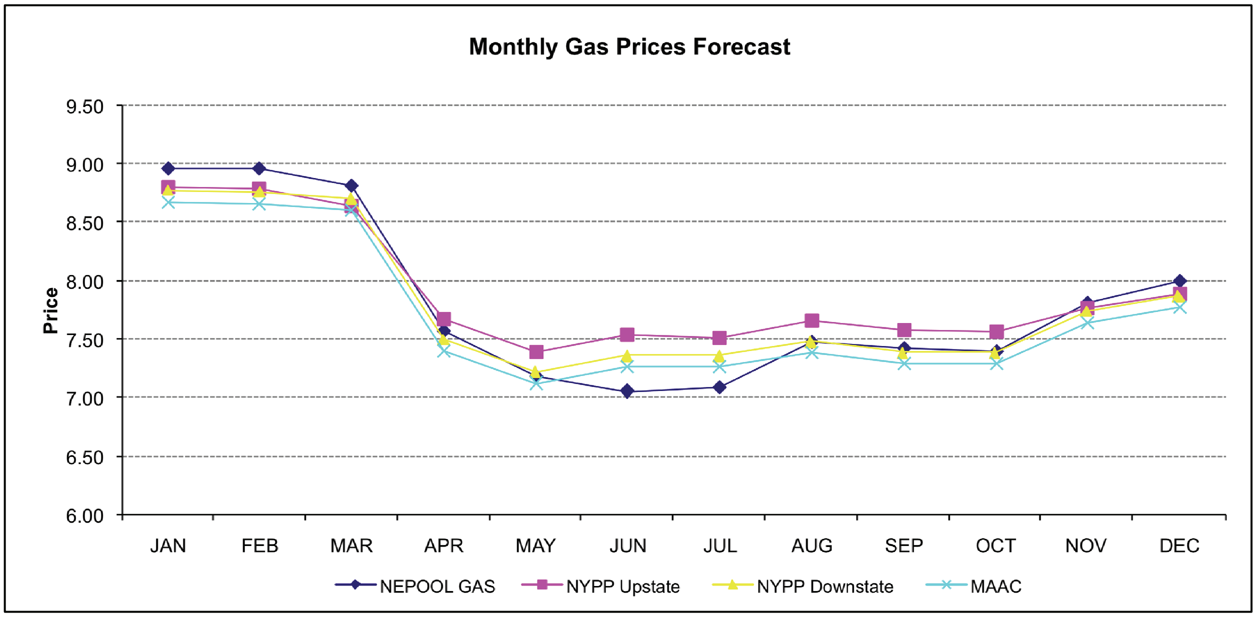
The GE MAPS model is considered to be the premier analytical tool for modeling the interaction of electric transmission and generation. The program simulates power system operations based on a highly detailed system model. Individual generating units are modeled in terms of variable production cost contributors (fuel price, heat rate, and variable O&M) to determine the marginal (incremental) cost that unit would incur in supplying power to the grid. Sufficient generation is committed to satisfy load demand within the system control area and to satisfy operating reserve requirements. Operating flexibility characteristics (minimum and maximum power levels, minimum down time, etc.) are included to reflect limitations on individual unit operations. The transmission system is modeled in terms of the expected power flow that would occur as a result of the injection of power at each location and in terms of the limits that apply to the amount of power that can be transported on each line. A full security constrained dispatch is performed that recognizes transmission line flow under contingency conditions as well as normal operation.

Power demand is specified for each of the 8,760 hours in a year and distributed between the various load buses in the system based on historical load patterns. The model uses a chronological, hourly simulation of system operations to capture the dynamic requirements imposed by hourly, daily, and seasonal changes in demand.

The GE MAPS operating model assumes individual generating units "bid" to supply power at their marginal cost of supplying power. A linear optimization process is used to determine the unit dispatch pattern that will minimize the total "cost" of supplying the power necessary to satisfy the load, subject to the constraints imposed by unit operating limits and transmission system limits. Based on the resulting dispatch pattern, the cost of providing an additional megawatt of power at each monitored location in the system is determined, thus developing a location-based marginal price (LBMP) that fully reflects the transmission system congestion cost that exists during that hour. The resulting LBMP, combined with the predicted dispatch, determines the revenue a generating unit can expect to receive from a perfectly competitive wholesale energy market.

This analysis used the year 2008 system to model the impact of wind generation and CAES on the utility system. The New York ISO was fully modeled, along with the New England and traditional PJM systems. Neighboring systems beyond the three interconnected ISOs were represented with simplified models. Gas prices were assumed to be roughly $8.00/MMBtu on an annual basis with monthly variations of up to +/- $1.00/MMBtu.

Figure 4: Gas Prices



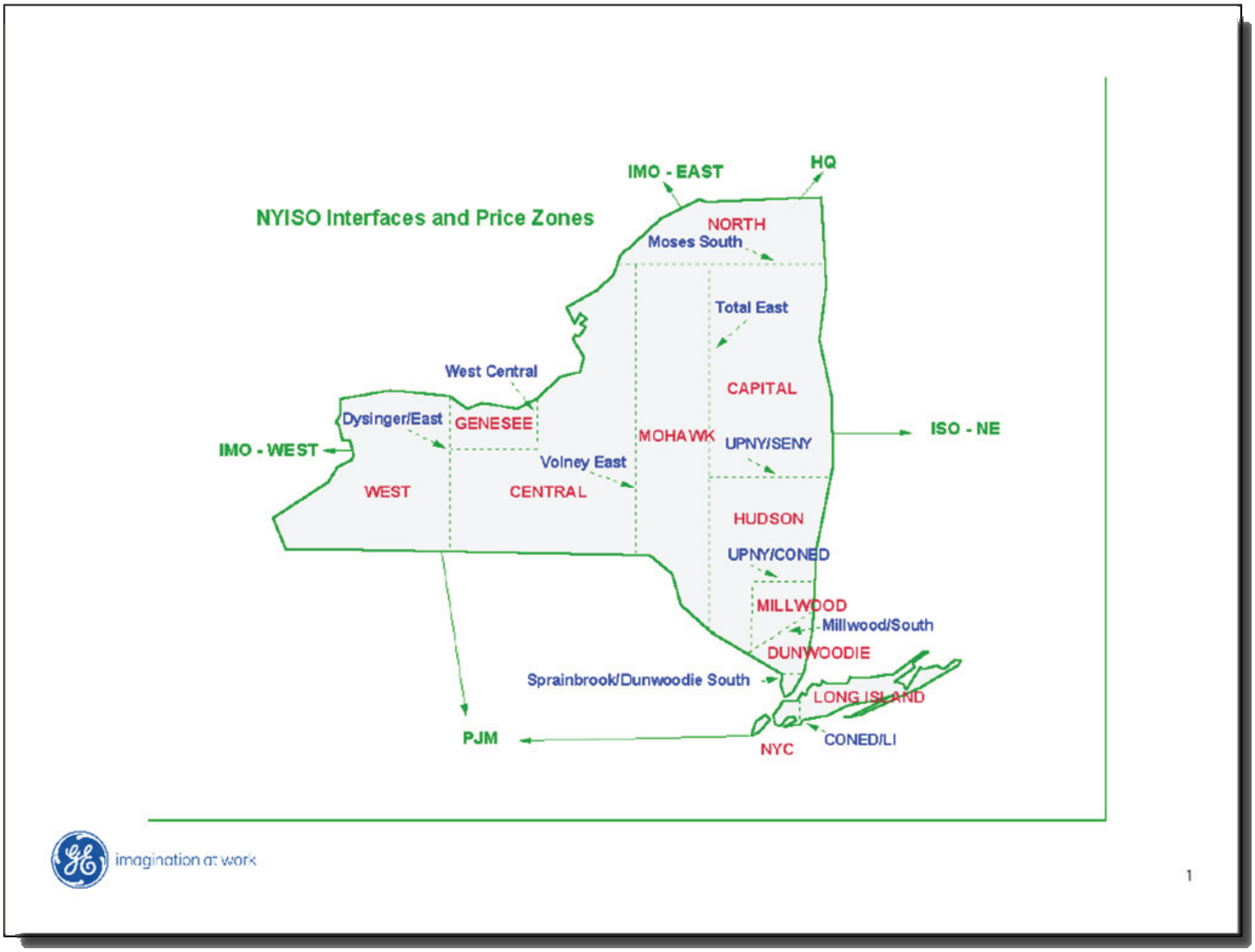
## 3.3 Analysis Results

Wind generation was added at four locations throughout the state. They could be considered as potential sites for wind/CAES co-location, however, since the mini-CAES projects do not alter the system analysis, the mini-CAES location can be optimized without changing these results. The wind sites also represent a reasonable estimate of the likely wind development, which was required in the MAPS runs. Table 1 shows the location and size of the wind sites.

Table 1: Wind Project Potential

| NY Zone | Energy (GWH) | Capacity (MW) | Capacity Factor |
|---|---|---|---|
| Mohawk (E) | 890 | 300 | 34% |
| West (A) | 298 | 110 | 32% |
| Hudson (G) | 126 | 50 | 29% |
| Long Island (K) | 1,125 | 300 | 44% |

Figure 5: Wind Sites

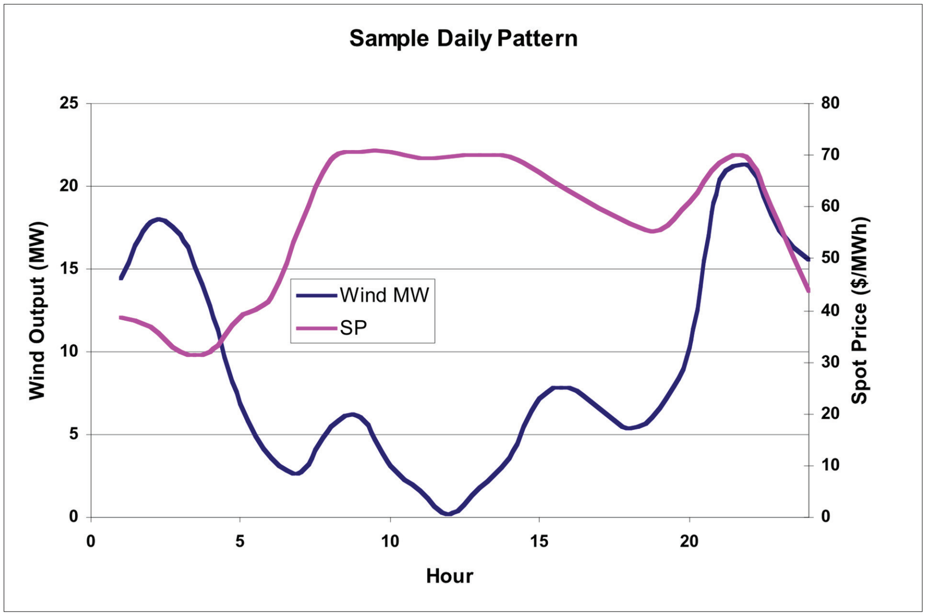


Hourly generation and spot prices were developed from the simulation of the NYISO system. Table 2 shows the annual average and range of the spot prices for the four sites as well as an additional site in New York City.

Table 2: Spot prices for Selected Sites

| NY Zone | Minimum ($/MWh) | Average ($/MWh) | Maximum ($/MWh) |
|---|---|---|---|
| Mohawk (E) | 16 | 52 | 86 |
| West (A) | 16 | 52 | 86 |
| Hudson (G) | 16 | 55 | 91 |
| Long Island (K) | 16 | 76 | 150 |
| New York City (J) | 16 | 56 | 150 |

Figure 6: Sample hourly results (Hudson)



As can be seen, the wind generation is largely out of phase with the value of the energy. The hourly wind profile and spot price patterns were developed for each of the sites and passed along for analysis with the CAES plants. Three compression versus generation time ratios for the CAES plants were examined to maximize the value of the low priced energy by effectively shifting it to the more desirable time periods. The ratios were one compression to two production hours, one compression to one production hour, and two compression to one production hour. A ratio of one to one represents a sizing of equipment where it takes one hour to fill a unit of storage that will provide compressed air for one hour of production.

The spot prices at a location represent the value of the energy at that location. If the storage is located remotely from the wind generation, then it is the spot prices at the storage locations that determine its value and not the spot prices at the wind locations. When there is no transmission congestion, then the prices will be the same, but when congestion exists then the prices will be higher in the load pockets. For storage facilities in a location removed from the wind sites to contract for wind energy output, it would be necessary for them to also purchase Financial Transmission Rights (FTRs) which would compensate the storage location for the spot price differences. Co-location of the wind and storage would avoid this expense. However, the generation of energy from the wind site is out of phase with the peak hours and therefore the transmission to move power into Zone J is predominantly required during off-peak hours, when it is usually available without the cost of FTRs. Our analysis assumed no cost for FTRs.

Previous analysis has shown that the New York system could handle the installation of wind generation up to 10% of the system peak load. The higher the wind penetration, the more desirable the storage devices will be since the higher penetrations will increase the frequency of extremely low off-peak prices.

## 3.4 Methodology for Additional[6] Values for Mini-CAES

The project focused most of the effort toward determination of spread value, primarily because it is the one form of value that is both universally accepted and simple to monetize. Other forms of value were examined and problems were found with all but capacity allocations.

We then sought data on alternative forms of value from a literature search and repeated efforts to contact and discuss the study with representatives of Consolidated Edison. The resulting methodologies were very simple, in part because it became apparent from the advice of Consolidated Edison that even if other values are provided to the system, the projects are too small to be material to a large densely meshed system. Upon further examination it became apparent that it is probably not possible to monetize most forms of value from a mini-CAES project. This issue is discussed further.

### 3.4.1 Deferred Transmission / Distribution Construction

We anticipated that a key reason to place a mini-CAES facility would be to add stability and possibly reduction of losses to a location. It was further reasoned that the most likely locations to benefit from mini-CAES are that those sites that have deficiencies and often a construction project might be planned to

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[6] “Additional” to the spread energy value which methodology was previously discussed.

provide a long term larger scale resolution. If such an expansion is expensive and can be deferred for a few years, the savings from that deferral should be recognized in the project decision.

This value was estimated in two ways: (1) by contacting Con Edison and (2) by calculating the value of a deferral of a theoretical distribution project.[7] Con Edison assigned no value for this service. The theoretical calculation is contained in a later segment, but we recommend that a developer ignore this concept unless it is accepted by the utility at the location.

### 3.4.2 System Support Services

Traditional ways to value stability for large scale CAES facilities include (1) comparison to operations at the McIntosh facilities, pumped storage hydro, or other hydro projects in both stand-by and synchronous condensing mode, (2) consideration of the long term maintenance costs associated with cycling various types of generation projects that could see reductions in costs through the operation of CAES units, and (3) recognition of system support values for which CAES would be well suited to serve.[8] None of these methods are appropriate for a small scale plant such as mini-CAES.

Con Edison advised in late October 2005, that the unit is too small to have significant benefits for preventing urban blackouts, system restoration, and operating reserves. In the face of this objection, all system support values were deemed not applicable to mini-CAES at this time, as stated.

This assignment of zero value in the “real world” contrasts with the early report of the project in October 2005,[9] which was given at a time when only the theoretical value was available. As the project progressed, we determined that projects would require quick “plug and play” capability and widespread use to approach economic viability. Therefore hard to monetize value was dropped from consideration.

### 3.4.3 Capacity

The mini-CAES facility provides a capacity product that can be entertained as two separate components:

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[7] This calculation borrowed heavily from the concept and examples presented in “Valuing DG as a Distribution Alternative – Computing DG Value, Summary Results for SCE 2003 sample projects”, prepared for E2I by Snuller Price, Energy and Environmental Economics, Inc (E3), draft 7-8-04.

[8] See also “CAES-Plant Cycles for Substation Application”, October 1997, Nakhamkin, Michael; Andersson, Lars; Potashnick, Boris; Swenson, Eric; Energy Storage and Power Consultants; prepared for EPRI, EPRI Project Manager Robert Schainker.

[9] Mini-Compressed Air Energy Storage for Transmission Congestion Relief and Wind Shaping Applications. (Prepared for New York State Energy Research and Development Authority), presented to EESAT 2005 Electrical Energy Storage Applications and Technologies, was a mini-paper demonstrating the early findings of this project.

- Conventional generation capacity with specific rapid response characteristics (that can, in some jurisdictions, be considered a renewable capacity source)
- Ultra-fast response capacity, from shutting down the compressor when it is operating

The facility can provide conventional or green capacity of 10.5 MW plus the compression capacity of ~15 MW additively, during the hours that the compressor is running. However, there are strict limits on the length of time that either or both types of capacity are available. A mini-CAES facility has only a few hours of energy storage, and when the compressor is running it is probable that the amount of storage is partially empty. Conversely, when the storage is nearly full, the compressor is unlikely to be running and in any event is limited those hours when energy (and usually capacity) is least desired, in normal operations.

These products are traded in the New York market, but the products are bid in for a monthly block at a single capacity value that is to be available at any point of the day. In order to reflect these operating restrictions, the facility can only bid the conventional 10.5 MW of capacity. Even this value may be questioned, as it is only available for a limited number of hours, related to the minimum number of hours of stored air that will remain after the facility has been drained. In the October 2005 mini-paper, the value assigned for capacity was measured from the total of generation and compression capacity. In this paper, that value is reconsidered to recognize only the base capacity of 10.5 MW.

### 3.4.4 <u>Reduction of losses</u>

If a consumer wants wind energy delivered to Long Island or Manhattan, the mini-CAES facility will reduce losses. The energy is delivered to Manhattan during the off-hours, and generation occurs in the peak hours, which reduces the losses during that period.

However, the point of the exercise is to recognize value that would attribute to the project, and a mini-CAES project receives no compensation for losses other than the hourly purchase and sale prices from the dispatch model. Therefore, this has no recognized value.

### 3.4.5 <u>Wind Storage</u>

Analysis of the energy quantities brought into question the concept of using mini-CAES to store wind energy for firm redelivery.

There are other studies[10] available that analyze the value of using CAES for wind storage and redelivery. Ridge Energy Storage and Grid Services is an industry leader in the development of analysis tools to

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[10] "The Economic Impact of CAES on Wind in TX, OK, and NM", Final Report, June 27, 2005, Prepared by Ridge Energy Storage and Grid Services, L.P. for the Texas State Energy Conservation Office.

develop understanding of the value of these systems. Large scale CAES provides greater storage periods at much lower unit cost.

The highest value for use of mini-CAES and wind was to locate in the urban centers where:

1. The renewable resource can be acquired during the night when transmission is more available
2. The value for the resource can be enhanced through production during peak hours
3. The resource can be dispatched

Analysis determined that during the 2005-2006 study period, the market does not offer any incremental value for green energy delivered via this mechanism than it does for green energy produced on site and consumed generically.

### 3.4.6 Summary of Incremental Value

The methodology for determining incremental value provided a significant disappointment for the project. In full-scale CAES projects there is usually a frustration around the difficulties of (1) obtaining objective data to recognize the incremental value of the storage, and (2) difficulties around obtaining contracts or market recognition for the value.

This study found that with mini-CAES, there is a clear issue around whether such values are meaningful in this smaller scale. To repeat for emphasis, the distinction is that with full scale CAES, there is clear value but problems with monetization, while with mini-CAES it is not clear that the value exists in a practical way.

We believe that in order to monetize additional value, a developer would have to identify a user that would benefit from the enhanced stability and arrange for suitable contracts, rather than seeking recognition in the broader power market.

No real world example has been identified of where such a value may be found. Perhaps a small urban center may prefer a reasonably high quality of power to attract commerce or a large secure data center. However, in the United States we enjoy good quality power in most locations and there may not be many places where the power quality strengths of mini-CAES could be valuable.

Therefore, this paper focuses on the mini-CAES design and the time of day power value that is compatible with the design in power markets over widely dispersed locations.

# 4 MINI-CAES SPECIFICATIONS AND EQUIPMENT SELECTION

## 4.1 Equipment Selection Background

The concept of a small scale CAES plant has been proposed and studied at various levels of detail by several parties in the past. Current design issues, the need to update the costs of material, and the detailed engineering that has occurred in storage systems suggested viewing the small scale CAES (mini-CAES) concept from the perspective of a fresh start exercise.

The study of New York wind resources overlaid on the NYISO energy market indicated that a relatively small storage interval of five (5) hours combined with a longer generation interval of nine (9) hours produced the highest value for the mini-CAES facility. There was consideration given to whether dispatch or capacity values for wind were appreciated more than for fossil or nuclear electrical power and whether that would impact design. We found that this was a distraction from our task. Individual retail marketers may find some value, but that there is no demonstrated value or market for such services beyond the provision of green energy.

With the above issues in mind, rates for injection and withdrawal from storage were developed along with an optimal volume of storage to support operations in that range.

## 4.2 Cycle Description

As noted in the introduction to this paper, the CAES concept basically is a cycle with two major sections; the first being air compression and storage, and the second being extraction of the stored air, mixing with a fuel in a combustor, and expansion across a turbine to generate power. Some heat recovery for overall economy of fuel use is also integrated into this section of the plant. The idea is to ‘store’ energy in the form of compressed air during times when power on the grid is at low demand (and cost); and then use the stored energy to generate power during peak rate or value times.

## 4.3 Concept Parameters and Components

Mini CAES is an attempt to take the Compressed Air Energy Storage concept, demonstrated successfully in at least 2 larger (>100MW output) commercial plants and numerous papers, to a smaller level of output where it may prove useful to store randomly available wind energy and/or meet peak requirements in either the production area or the consuming region. A nominal size of 10MW to 20MW output was initially selected.

A focused effort was made to find machinery that was developed for other uses and apply it to the requirements of the overall CAES cycle. The most challenging component proved to be the expander driving the generator, which will be exposed to both high temperature (~1500-2500°F) and high pressure (500-1000 psig). The choices from machines proven in current industrial applications appear to be limited to either power recovery turbines from the process industry (Nitric Acid or Ethylene Oxide), or currently available combustion turbines used for either power generation (driving a generator) or as mechanical drives for pumps, compressors, or other large industrial loads. We recognized that it might also be attractive to utilize a steam turbine adapted to this lower power and flow CAES cycle, but did not follow this choice.

The initial review of available ‘expander turbine’ hardware determined that the power recovery turbines from the process industry have proven operating design limitations in the area of 1400-1500°F and 300-350 psig as inlet parameters, and generate as much as 30,000 HP in output. The proven combustion turbine designs can accommodate firing temperatures in the 2200-2500°F range, which are much higher; but the smaller size (lower output) machines are limited in pressure capability to 150-250 psig at the inlet. Based on a high level engineering review that was performed, for the initial plant sizing, a Mercury 50 model machine was selected because the name plate rating of ~ 4500kW at ISO conditions fit the study target 10 MW-20MW nominal output when de-coupled from the compressor. This machine has nominal inlet conditions of 41.5 lb/sec of air at approximately 140 psig. In addition, the standard M50 design includes a recuperator, which uses the turbine exhaust energy to pre-heat the combustion inlet air, thus increasing overall power generation system efficiency.

Compressors to provide air at the required rate at 150 psig and even to 600 or 1200 psig are readily available from several world-wide suppliers. Team member Dresser-Rand is a world class compressor supplier and has participated on existing CAES plants as well as numerous CAES plant studies.

Another major component selected in the first engineering review was the choice of above ground storage cylinders in an effort to make the plant location very flexible. Larger CAES facilities require use of underground salt caverns or aquifers as reliable storage of the compressed air energy geotechnical restrictions, but such geotechnical restrictions are seen as undesirable for the small scale CAES that might be repeated at a variety of sites. A standard storage vessel design from an application designed by EnerSea Transport was selected with a capability of 1,200 psig containment. This approach was chosen because of prior work completed analyzing a combination of vessel cost, primarily related to volume, and wall thickness to meet Code requirements and total space required for the storage.

The proposed air storage system utilizes proven technology consisting of numerous short lengths of large diameter pipe connected by manifolds resulting in an arrangement of tiered pipe tanks. The arrangement and number of tanks can be configured to optimize the loading rate, unloading rate, and storage volume parameters as required for any specific application.

The storage system is custom designed and site constructed. Construction of the storage facility encloses the pipe tanks within a steel skeleton frame that also contains internal steel grillage for strength and support. The exterior of the structure would be clad with pre-cast concrete panels attached to the steel frame members. Overall, approximately two-thirds of the structure will be buried for stability and safety. The cost estimates assumed that the selected site has sufficient earth cover to make the required excavation without encountering extensive rock, which may be an optimistic assumption at many New York City locations.

The tiered pipe tanks are constructed from individual lengths of 42” diameter pipe segments fabricated into 120’ lengths. Hemispherical end caps with appropriate pipe nozzle components are then welded to the pipe segments. The completed pipe tanks are then positioned vertically and connected to a series of manifolds and header pipes as required to produce the tiers needed to meet the site-specific conditions.

The equipment required for loading and unloading the storage system with compressed air is arranged and located adjacent to the storage structure in the same general area as the generation equipment. Again, proven technology components such as air compressors and pumps with appropriate drivers, displacement fluid storage, and appropriate control devices will be utilized. These components allow the storage system to be loaded and unloaded at constant pressure conditions, thus optimizing equipment design and performance variables.

The overall design philosophy of the storage system is based on CFR Part 192 – Transportation of Natural or Other Gas by Pipeline –Minimal Federal Safety Standards and ASME B31.8, “Gas Transmission and Distribution Piping Systems”. These requirements are intended to cover the storage of high-pressure natural gas in buried service and should be conservative when applied to air. At the time of the study (2005-2006); EnerSea Transport was in the final stages of obtaining approval from the U.S. Coast Guard to utilize this technology for ocean transportation of natural gas and delivery of that gas to U.S. ports. Local approval from the appropriate Code authority will be required for any storage system built.[11]

An item not addressed in this study deals with the corrosion issues associated with storing air in pipes. While there are industry standards and methods that address this problem such as protective coatings, corrosion inhibitor treatments, material selection and etc., none of these options have been explored for this application.

Rather than ‘waste’ the energy represented by expansion of that high pressure stored air, the next major component selected was a ‘topping turbine’ from current industrial steam turbine technology. This was added to generate some power letting the stored air down to the required pressure at the inlet of the standard combustion turbine. A second recuperator was also added to use the remaining heat energy in the exhaust gas coming from the standard Mercury recuperator at ~665°F. As a preliminary attempt to optimize the heat balance around this section, a small amount of fuel was added in a combustor ahead of

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[11] If approval to build using the specified codes were declined it is likely that the alternative design will be more expensive. Under ASME pressure vessel codes the costs for the pipe storage are expected to increase by 2 – 2.5x. However, approval is anticipated for marine applications where storage, the ship, and crew lives are in close proximity and so Ridge expected that this service may be approved. Some team participants expect ASME codes to prevail.

the topping turbine to provide a discharge temperature at the appropriate level to make use of the waste heat available from this second recuperator.

A final efficiency addition is the use of liquid displacement to remove the air in the storage cylinders during the expansion cycle. This concept uses a liquid storage tank and pump, piped and valved with controls to maintain a constant pressure of 1200 psig on the turbine while the expansion cycle is in operation.

The overall cycle diagram for this equipment lineup appears as follows in Figure 7, showing the Air Compression and Storage side of the cycle, and Figure 8, showing the Generation Plant. Pressures, flows, and temperatures indicated are nominal and basically set by the selection of the Mercury 50 turbine parameters. Some alternative approaches are described in a later section of this report.

Figure 7: Mini-CAES Compression/Storage

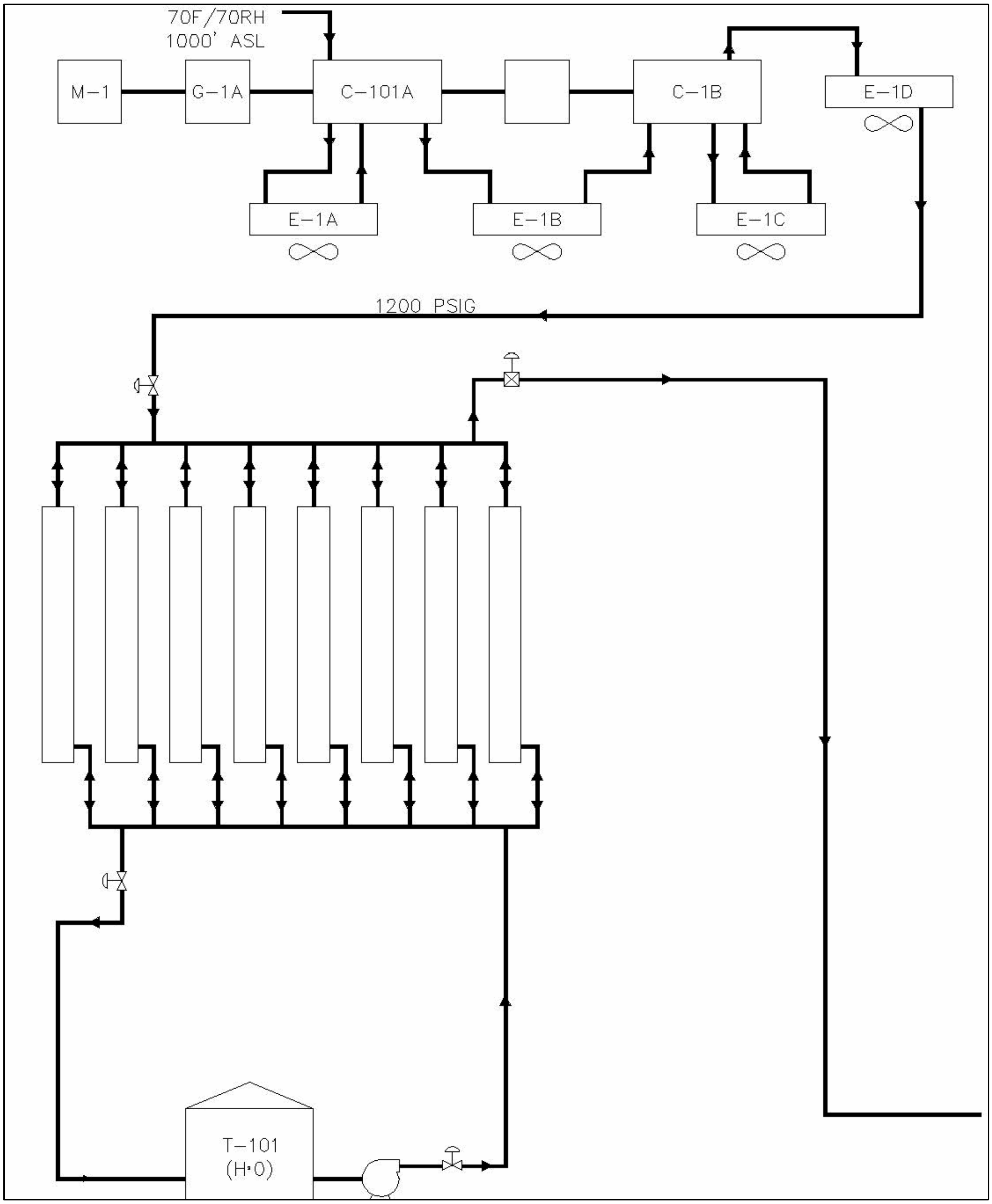
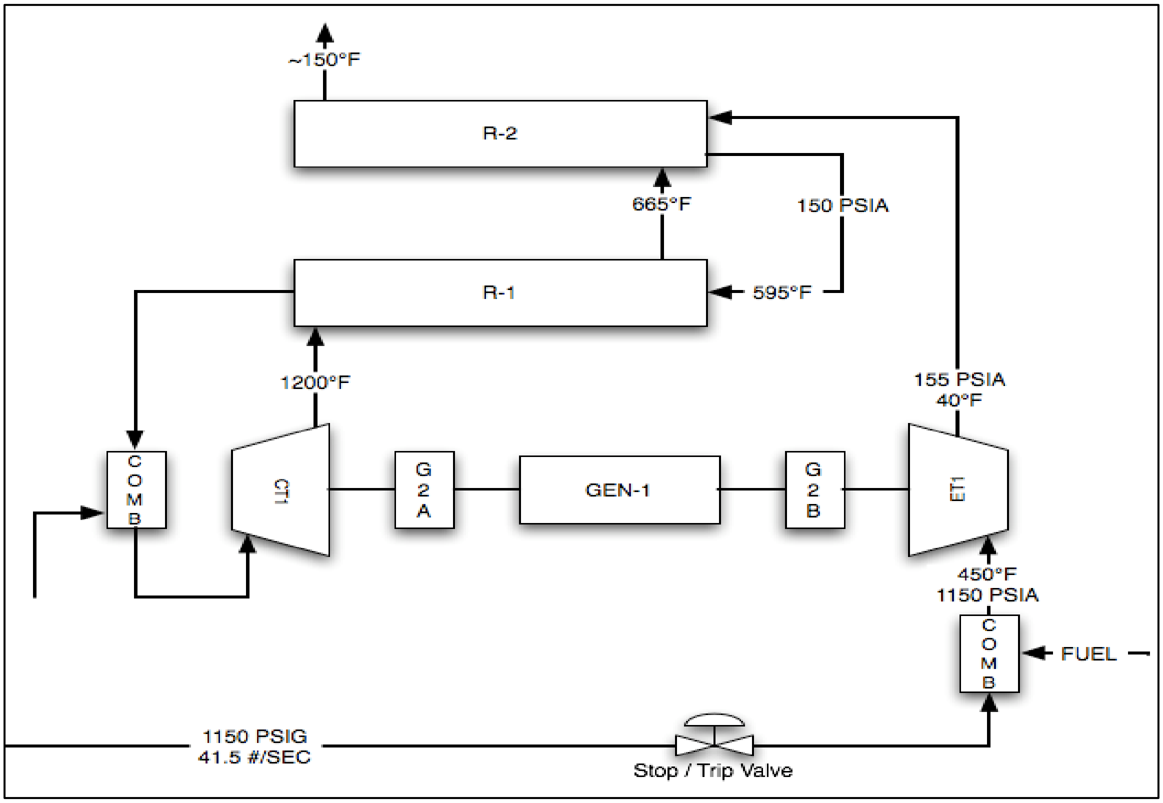


Figure 8: Mini-CAES Generation



## 4.4 Specification Development and Requirements

The conceptual design for this facility required two types of specifications to be developed for the major equipment. The first are the performance specifications, which include flows, volumes, pressure levels, fluid characteristics, etc. to be accommodated by the equipment during operation. The other specifications to be identified are the Industry standards such as ANSI, ASME, API, etc. which describe the minimum mechanical and operating requirements for the equipment.

The Industrial or other codes for the remaining equipment can be found in ANSI or API/ISO standards for pumps, compressors, and drive turbines. The compressors and the power turbines are built to manufacturers' standards that conform to API standards for these machines, but not all requirements are met; nor do they need to be for this application.

The general performance requirements for these machines were initially selected based on the requirement that sufficient mass for nine hours expansion through the standard Mercury 50 turbine must be compressed within four to five hours time. The nominal parameters are:

Table 3: Equipment Specification

| Item | Flow-lb/sec | Inlet Psig/°F | Disch. Psig | Misc. |
|---|---|---|---|---|
| Air Compr. | 75. | 0 #/70°F | 1200/300°F | |
| HP Turbine | 41.5 | 1200#/500°F | 150#/50°F | |
| LP Turbine | 41.5 | 150#/2100°F | 0#/1200°F | |
| Recuperator 1 | 41.5 | 0/1200°F | 0/600°F | |
| Recuperator 2 | 41.5 | 0/600°F | 0/200°F | |
| Air Storage | 75 in/42 out | 1200#/300°F | Constant | 230,000 ft $^3$ |
| Water Pump | 23,000 gpm | 0 psig/90°F | 1200# | |

### 4.5 Plant Performance

A preliminary estimate of plant overall performance was made using the equipment with nominal capacities and specifications as noted in the above section. In summary, the base plant, using five hours for storage of sufficient air to generate (expand) over nine hours time is as follows:

- Heat Rate ~4100-4150 Btu/kW-hr (LHV)
- 10-10.5 MW Generation Output (net-over 9 hours)
- 15-16 MW Compression Input (gross-5 hours)
- Storage at 1150-1200 psig
- Energy ratio of 0.88

The heat rate does not include the required power from a nearby wind farm or other low cost source to power the compressors during the storage portion of the cycle. The required power for the water pump providing constant pressure to the system is approximately generated by the HP topping turbine, resulting in a net generation as provided by the Mercury 50 commercial turbine generator set.

### 4.6 Capital Costs-Base 5:9 plant (5 hours injection: 9 hours generation)

A conceptual level cost estimate was developed to include the engineering of the basic plant, the major equipment, and the necessary plant piping and control systems for reliable operation. This included consideration of intermittent service (daily starts and stops) and budgetary level quotes from vendors for the major equipment vendors. A summary of these costs is included in Table 4 below.

Table 4: Factored Cost Estimate Summary (+/- 30%) – circa 2005

| | Equipment Cost ($000) | TIC ($000) |
|---|---|---|
| **Factored Costs** | | |
| Combustion Turbine / Generator / R1 Recuperator | 3,000 | |
| Air Compressor | 6,000 | |
| Expansion Turbine / Generator | 1,500 | |
| Air Compressor Air Coolers | 450 | |
| Air Compressor KO Drums | 100 | |
| Water Storage Tank | 990 | |
| Recuperator | 570 | |
| PV-1 (Air Storage Vessels & Water Pump) | 5,333 | |
| Sub-Total Factored Costs | 17,943 | |
| Installation (50% for Gulf Coast or Upstate) | 8,972 | **26,933** |
| | | |
| **Non-Factored Costs** | | |
| Control Room / Admin Building | | |
| PLC / Safety System | | |
| Instrument Air System | | |
| Site Work | | |
| MCC | | |
| Spare Parts | | |
| Sub-Total Non-Factored Costs | | **3,440** |
| | | |
| Sub-Total Direct Costs | | **30,373** |
| | | |
| **Indirect Costs** | | |
| Construction Management | | |

Table 4: Factored Cost Estimate Summary (+/- 30%) – circa 2005

| | | |
|---|---|---|
| Insurance | | |
| Engineering | | |
| Contingency & Fee | | |
| Sub-Total Indirect Costs | | **12,800** |
| | | |
| **Total USGC** | | **43,173** |
| | | |
| Labor Adjustment to Long Island | | **12,299** |
| | | |
| **Total** | | **55,472** |

### 4.6.1 Capital Cost Summary

The above Capital Costs are considered in the following unit values to allow easy comparison to other projects.

Table 5: Cost Summary ($/kW)

| | **Upstate** | **Long Island** |
|---|---|---|
| Combustion Turbine / Generator / R1 Recuperator | 290 | 290 |
| Air Compressors / Motor Drive | 620 | 620 |
| Recuperator R2 & AC Intercoolers/drums | 50 | 50 |
| Topping Turbine / Generator | 140 | 140 |
| Water Tank / Pumps | 90 | 90 |
| Air Storage Pressure Vessels[12],[13] | 510 | 510 |
| Installation[14] | 850 | 2,030 |
| Non-Factored Costs | 330 | 330 |
| Subtotal Costs | 2,880 | 4,060 |
| Indirect Costs[15] | 1,220 | 1,220 |

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[12] As noted, design to ASME code as a pressure vessel instead of a pipeline code would increase costs by 2.5X.

[13] The Upstate total installed storage cost is $760/kW and the Long Island total installed storage cost is $980/kW.

[14] Installation costs are controversial because the estimates do not fully reflect modular plug and play designs that could apply to non-storage equipment.

| Table 5: Cost Summary ($/kW) | | |
|---|---|---|
| | **Upstate** | **Long Island** |
| **Total** | **4,100** | **5,280** |

### 4.6.2 Comparisons of Storage Capital Costs to "EPRI Study"

However, these costs differ significantly from a prior study and are in fact contentious within our study group. The following presents two separate comparisons to arrive at a better understanding of the range of reliability of the estimates and the specific areas of clarity and disagreement within them. In summary there are two issues:

1. The storage figures are based on approval of a pipe design code to withstand above ground air pressure service, instead of the ASME pressure vessel codes. The estimates, as detailed above, are based on the pipe codes that some of the authors believe are close to acceptance for marine service and therefore may be accepted for on-land service, for air storage only.
2. The project costs included very large allocations for project design engineering, management, and general construction costs. Some participants felt that these costs were needed for this type of facility, while others believe that the facilities can be standardized and modularized, eliminating much of that cost. This topic is discussed in section 4.7 "Alternative Construction".

We reviewed the study "CAES-Plant Cycles for Substation Application", October 1997, Nakhamkin, Michael; Andersson, Lars; Potashnick, Boris; Swenson, Eric; Energy Storage and Power Consultants; prepared for EPRI, EPRI Project Manager Robert Schainker ("EPRI Study"). The excellent study ran extensive costing scenarios for different sizes of surface CAES facilities with different designs. The comparison is broken into two segments (1) storage and (2) the balance of the plant. For our purposes we compare only our pipe storage design for recuperated cycle to their pipe storage design for recuperated cycle.

The EPRI study did not consider a Long Island urban construction possibility, so our review compares the Upstate New York costs to their generically sited costs.

In 2006-dollars an installed cost for nine hour storage (prorated from three, five, and 10 hour storage values) under the EPRI paper is about $570-595/kW. This would be comparable to the Upstate value of $760/kW (installed) in this study. The Volands design has been extensively optimized and vetted via the Enersea development company studies and was conducted at the more recent time frame (2005-2006).

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[15] Indirect costs are controversial because the estimates do not reflect the possible reduction of engineering and other "overheads" for a repeatable design and might be reduced for a modular design.

After review, our storage engineer felt that we should expect the costs to be closer to $760/kW for pipe storage at 1,200 Psig and the difference in cost is ~25%, which is not significant.

The EPRI study also compared a variety of storage mechanisms, finding that buried pipeline storage was the most cost effective. That supports the Volands technology, since it is using advances in code approval to use a “near buried” code design in a vertical configuration. This provides much greater storage capacity in a much smaller area of land.

Table 6: Selected Pipeline Storage Cost Comparisons

| **EPRI CAES-Plant Cycles for Substation Application**<br>**$/kW** | | |
|---|---|---|
| Recuperated cycle, pipeline storage | Table 5-20 [15.9-20.5 MW] | Table 6.1 [15.9MW 3 hour] |
| Psig | 1,000 | 1,000 |
| EPRI; 1996 3 hours | | 155 |
| EPRI; 1996 5 hours | 254 | |
| EPRI; 1996 10 hours | 491 | |
| Prorated to 9 hours from 5 and 10 hours for 15.9-20.5 MW scenaric | 444 | |
| Ratio to 9 hours from 3 for 15.9 MW 3 hour scenario | 465 | |
| Inflated at 2.5% p.a. to be **$2006** | | |
| Prorated to 9 hours from 5 and 10 hours for 15.9-20.5 MW scenaric | 568 | |
| Ratio to 9 hours from 3 for 15.9 MW 3 hour scenario | 595 | |
| **This study: 1200 Psig, Upstate Installed Cost, Pipeline Code** | **760** | |

## 4.7 Alternative Construction

A second path of alternatives exists by varying the construction approach rather than (only) adjusting the equipment design. Consideration was given to how the design could be modularized into portable units, except the storage,[16] in order to reduce the site-specific engineering and construction costs. It is clear that with a concerted effort in this direction the costs per facility almost certainly could be dropped by a very considerable factor. The actual equipment costs are in the order of one-third of the budgeted figures, so it is reasonable to believe that a 50% reduction in cost is feasible.

Examining Table 5 – Cost Summary confirms that 50% is a valid sensitivity scenario. If we take the $4100/kW upstate cost and subtract both the Indirect and the Installation costs, we end up with just about one-half the original cost. Although we assume that a plug and play unit will still have some installation costs, taking this data as a whole, it seems that 50% is a reasonable first estimate of a lower boundary condition.

Are dramatic cost savings a reasonable expectation? The equipment could be designed so that all components except the storage facility are “plug and play”. Generation and compression equipment in significantly larger sizes than this have been designed and produced in trailer mounted packages that can be assembled and placed in service in hours. Quick assembly construction of the storage could also have a very significant impact on the Long Island and New York City locations, where the labor rates are estimated at about 2.5 times an upstate location. However, savings on storage may be limited because

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[16] Storage is a repetitive modular system, but it requires local civil and geotechnical design in any event.

some piecework construction was planned and included in the project cost estimate and a significant majority of the budget costs are related to the bulk cost of steel, welding, and assembly costs, none of which be eliminated by replication. In total, though, savings are expected for storage, compression, and generation packages, and it is a reasonable sensitivity.

### 4.7.1 Comparison of Overall Project Costs to EPRI Study

Having arrived at the above analysis independently, the overall project costs were then compared to the EPRI Study. The cost comparison was superficial and the reader should be cautious in drawing conclusions. Nevertheless, we found that equipment costs alone are nearly double the 1997 estimated values, with both expressed in 2006 dollars. We do not believe it is possible to purchase the major equipment packages at materially lower prices than quoted for this study; therefore, we believe that the EPRI Study understates the costs of mini-CAES today.

However, we are equally certain that while this study presents a valid and reasonably detailed estimate, it is reasonable to assume that a determined party can find less expensive ways to accomplish the same construction. The challenge is to find a reasonable boundary for the sensitivity. Therefore the following Table 7 presents a summary of the EPRI Study costs in the top section and a listing of the total NYSERDA study costs in the lower section.

Table 7: Selected Project Cost Comparisons

| **EPRI Study - 1997** | **Table 6-1 15.9 MW Recuperated Cycle** | | |
|---|---|---|---|
| | **Plant Capital Costs ($/kW)** | | |
| | **Study Values** | **Scaled Storage** | **2006 $** |
| Storage - 3 hours | 155 | | |
| Storage - 9 hours equivalent | | 465 | 595 |
| Equipment: Turbomachinery | 170 | 170 | 218 |
| Turbomachinery modifications | 48 | 48 | 61 |
| Compression and Heat Rejection Equipment | 79 | 79 | 101 |
| Heat Recover Equipment | 38 | 38 | 49 |
| Equipment Costs | 9 | 9 | 12 |
| Equipment Erection Cost | 17 | 17 | 22 |
| Total Plant Cost | 516 | 826 | 1,057 |

| **NYSERDA 2006 Study Summary** | **2006 $** |
|---|---|
| Erected Costs | 2,550 |
| Erected plus Non-Factored Costs | 2,880 |
| Erected plus Non-Factored plus Indirect Costs | 4,100 |

Considering the above boundary case and the core estimate, this study (NYSERDA) found costs for an upstate location to be approximately $2,550 - 2,880. Even the lower boundary case, which might be more reasonable in our view, is about double the costs of the EPRI Study. Even though this NYSERDA study includes some costs that can be reduced, we believe that an actual facility would be somewhere between the $2,550/kW lower bound and the $4,100/kW upper bound presented here. If the pipe storage system has to be designed to meet ASME code requirements, even $4,100/kW may not be an upper bound.

### 4.8 Alternative Plant Configurations

In view of the apparent high capital costs and non-competitive nature for the ‘base case’, two alternative plant configurations were briefly investigated to determine possible capital cost savings and/or improved plant output. The first alternative configuration looked at a cycle based on compression/storage at ~160 psig, leaving the timing at five hours compression to produce sufficient air for nine hours production. This configuration reduces the overall compression power to ~ 12,500 horsepower (9325 kW) and reduces the capital costs by some $6 to 7 million (installed) for the smaller compressors and elimination of the ‘topping turbine’ of the base case. However, neither the air storage vessel nor the water pump and tank costs are reduced because at this lower pressure, the volume to be stored increases by ~7 times. In addition, the ~1.5 MW of power to drive the water pump maintaining constant pressure in the turbine is no longer offset by the expansion turbine so the net plant output is reduced to 9.0 MW. The overall economics for this case do not appear competitive.

The other configuration alternative investigated was a ‘mid-range’ cycle design for air compression and storage at ~600 psig. While this approach reduces the compression power and costs somewhat, it does not provide the level of economic benefit apparent in the first alternative cycle at 160 psig. Further details were not pursued.

The other way to reduce cost is to either have a longer storage period and a shorter, higher value electricity peak. While a variety of hourly configurations were investigated, none were found adequate at these locations. The nine-hour storage configuration provided benefits at the highest value Long Island location, especially after considering the need to keep some storage active if the project is to sell capacity.

### 4.9 Changes in Costs

Further, the budget estimates for this report were produced in late 2005 and early 2006. Since that time, the price of steel has increased and appears poised for continued rise.[17] This price rise may disproportionately affect the project because of the significant use of steel in the storage system.

### 4.10 Plant Emissions and Regulatory Considerations

The following is a summary overview of possible air permitting issues associated with installing a Solar Mercury 50 natural gas fired simple cycle combustion turbine at a Greenfield site at possible locations in

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[17] “Rising Costs Could Sap Steelmakers’ Profits, September 25, 2007, Robert Guy Matthews, Wall Street Journal. (Note: The study work was performed in 2005 and January, 2006, with the report being produced in Q1, 2008.)

upstate New York or on Long Island. The primary difference in the location of the turbine would be the status of the area in regards to attainment with the National Ambient Air Quality Standards (NAAQS). The primary criteria used to establish initial permitting applicability of a new installation is the potential to emit for that installation. For this overview, it is assumed that the only emissions source at the new facility will be the combustion turbine. As a basis for this analysis, emissions information from a Solar Turbines Incorporated paper titled *Mercury 50 Emissions Signature* with a 2004 copyright date was used. Table 8 below summarizes the key emissions information from this paper.

Table 8: Solar Mercury 50 Combustion Turbine Emissions

| Emissions | $NO_x$[1] | CO[1] | UHC[1] | VOC[2,3] | $PM_{10}$[2,4] | $SO_2$[2,4] | Formaldehyde[2,4] |
|---|---|---|---|---|---|---|---|
| ppm | 5 | 10 | 10 | 2 | | | |
| Lb/hr | 0.95 | 1.16 | 0.66 | 0.13 | 1.86 | 0.15 | 0.13 |
| tpy | 4.2 | 5.1 | 2.9 | 0.6 | 8.1 | 0.7 | 0.6 |
| Lb/MMBtu[5] | 0.023 | 0.028 | 0.016 | 0.003 | 0.0419 | 0.0034 | 0.00288 |
| Lb/MW-hr[6] | 0.20<br>(0.09) | 0.24<br>(0.11) | 0.14<br>(0.06) | | | | |

Notes:

[1] The $NO_x$, CO, and UHC emission levels represent the lowest allowable emissions warranty for natural gas in ppm.

[2] All other pollutant emissions represent estimates of non-warranted pollutant emissions.

[3] The VOC emission levels are 20 percent of the UHC levels.

[4] The referenced paper only includes the lb/MMBtu emission levels for $PM_{10}$, $SO_2$ and formaldehyde. The lb/hr values were calculated using a fuel input rate of 44.3 MMBtu/hr (HHV), as given in the Solar Turbine Incorporated paper. The tons per year (tpy) values were calculated assuming 8,760 hours per year of operation.

[5] The $NO_x$, CO, UHC, and VOC lb/MMBtu levels are on a LHV basis, while the $PM_{10}$, $SO_2$, and formaldehyde lb/MMBtu levels are on a HHV basis.

[6] the Lb/MW-hr rating was taken for the Mercury 50 gas turbine in normal service, which is a 4.6 MW machine in simple cycle driving a generator, with the values in parentheses being prorated for the ~10.5 MW output in this service, thus creating a more favorable emissions profile.

### 4.11 NSR/PSD Applicability

The federal Clean Air Act (CAA) New Source Review (NSR) provisions are implemented for new major stationary sources and major modifications under two programs: the prevention of significant deterioration (PSD) program outlined in 40 Code of Federal Regulations (CFR) 51 and 52.21, and the Nonattainment NSR program outlined in 40 CFR 51 and 52. If the proposed facility is located in an attainment or unclassifiable area with respect to all pollutants, the PSD program will apply to the Project.

The PSD regulations are designed to ensure that the air quality in existing attainment areas does not significantly deteriorate or exceed the ambient air quality standards (AAQS), while providing a margin for future industrial and commercial growth. PSD regulations apply to new major stationary sources and major modifications at existing major sources undergoing construction in areas designated as attainment or unclassifiable.

A PSD major stationary source is defined as any one of the listed major source categories which emits, or has the potential to emit, 100 tons per year (tpy) or more of any regulated pollutant, or 250 tpy or more of any regulated pollutant if the facility is not one of the listed major source categories. The proposed installation would not be considered one of the 28 listed major source categories, and it therefore would have a 250 tpy PSD major source threshold. Because the estimated potential to emit of each PSD pollutant, as shown in Table 1 above, is well below the 250 tpy major source threshold, the installation of the combustion turbine in an attainment or unclassifiable area would not trigger the requirement for a PSD permit, and as such would be expected to require a minor source construction permit.

The counties making up Long Island (Suffolk, Nassau, Queens, and Kings Counties) are designated nonattainment areas for the eight-hour ozone standard and the $PM_{2.5}$ standard. Locating the Project on Long Island would entail an applicability review for nonattainment NSR. In general, nonattainment NSR applicability is based on lower potential to emit thresholds than what is used for PSD applicability. Although a detailed review of the New York nonattainment NSR regulations was not conducted, based on typical nonattainment NSR threshold levels for a new facility, it is expected that the Project would not trigger nonattainment NSR if located in the Long Island area or in a nonattainment area in another part of New York.

### 4.12 NSPS Applicability

Regardless of whether a minor source or major source permit is required, the permitting effort will require a regulatory review to identify applicable federal, state and local regulations, and preparation of a permit application using the appropriate application forms and supplemental information. A preliminary regulatory review shows that the combustion turbine would be subject to either the New Source Performance Standard (NSPS) for Stationary Gas Turbines, 40 Code of Federal Regulations (CFR) Part 60, Subpart GG or proposed NSPS Subpart KKKK, Standards of Performance for Stationary Combustion Turbines. NSPS Subpart GG includes standards for $NO_x$ and $SO_2$ that should be easily met by the proposed project's combustion turbine. Proposed NSPS Subpart KKKK, if finalized as proposed, will apply to combustion turbines, which commence construction, modification, or reconstruction after February 18, 2005. If Subpart KKKK applies to a unit, then Subpart GG will not apply. The emission standards of Subpart KKKK are more stringent than Subpart GG, although it appears that the proposed combustion turbine would be able to easily meet the output based NOx standard of 1.0 lb/MW-hr included in proposed Subpart KKKK. The NSPS standards also include monitoring, recordkeeping, and reporting requirements.

### 4.13 MACT Standard Applicability

The maximum achievable control technology (MACT) standard for stationary combustion turbines is found at 40 CFR 63 Subpart YYYY. This MACT standard is only applicable to affected emission units located at a facility that is classified as a major source of hazardous air pollutants (HAPs). The definition of a major source of HAPs is a source that has a potential to emit 10 tons per year of any single HAP or 25 tons per year of combined HAPs. Based on the formaldehyde (largest HAP pollutant) and total HAP emissions information for the combustion turbine, the HAP emissions would be expected to be well below the major source HAP levels and as such, Subpart YYYY would not apply to the combustion turbine.

### 4.14 Emissions Summary

Due to the relatively low potential to emit levels associated with the Solar Mercury 50 combustion turbine, it is expected that the proposed installation would be considered a minor source under NSR permitting requirements. The new combustion turbine would be subject to a NSPS standard, but based on the emissions information available, it is expected that the new unit would be able to easily meet the NSPS emission limits. This analysis did not include a review of State or Local regulations that may affect the air quality permitting requirements for this type of installation.

The only other emissions anticipated to fall under regulation would be the potential noise from the air cooled exchanger fans, the compressors, and turbines under operation. It is expected that local noise regulations can be met with some ‘space’ for a non-urban site; or with appropriate levels of noise control equipment (insulation, directional inserts, etc.) for an urban site as required. Such controls are minimal cost to install and well within the accuracy level for the plant cost estimates provided above.

# 5 VALUE DEVELOPED BY THE MINI-CAES UNIT

The value of a mini-CAES unit was estimated as described in the methodology, which condensed to the following estimates of value:

Table 9: Mini-CAES Value Components

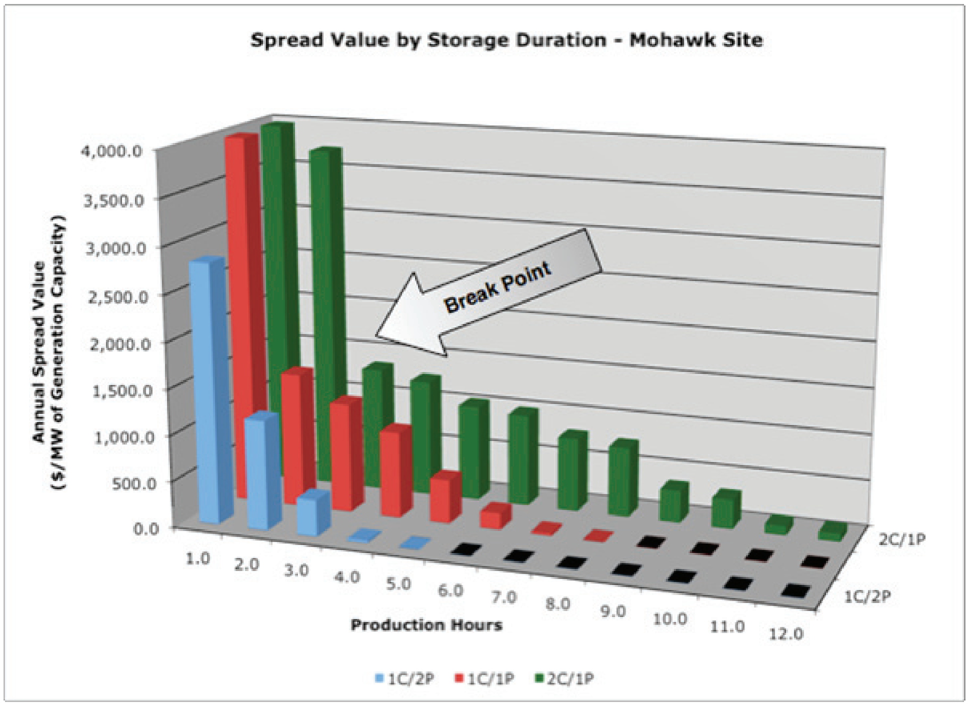
| Value Form | Contribution | Comment |
|---|---|---|
| Spread Energy | Buy power at low cost and generate at higher value periods | Detailed analysis performed |
| Capacity | Provide capacity to grid | Capacity price established by GE MAPS and reference to current ICap prices, with sufficient storage (nine hours) to provide capacity for at least a short period at any time |
| Deferred Construction | Zero value recognized | Calculation included, but probability of realization is low and probability that a significantly large project could be deferred is also low |
| System Support | Zero value recognized | Found that no value can be relied upon for most services |
| Reduction of Losses | Zero value recognized | No way exists to monetize this value. However, the spread energy prices implicitly recognize the value of loss reduction. |
| Wind Storage & Leveling | Zero value recognized | Co-location with a wind project can reduce the error between predictive dispatch and actual observed power generation sufficiently to reduce dispatch penalties to zero.<br>However, regulations changed to dramatically reduce these penalties, therefore making the value moot. |

The spread energy value was found to be the principle form of monetizable value. The project ran scenarios to understand design characteristics that maximized the dispatch value and compared the project locations to identify where the project value was maximized.

## 5.1 Scenario 1: Upstate New York - Mohawk

The following graphic displays the spread energy value under three scenarios of compression to production hours of operation. It shows that the value of the storage facility is enhanced by compressing roughly twice as quickly as the production occurs, but this tails off dramatically after the first hour. The greatest value is realized by compressing in the least expensive hour and producing in the most valuable hour. No allowance was made for less than perfect choice of hours to operate, so this represents an upper boundary on the spread energy revenue.

Figure 9: Spread Value by Storage Duration: Mohawk Site

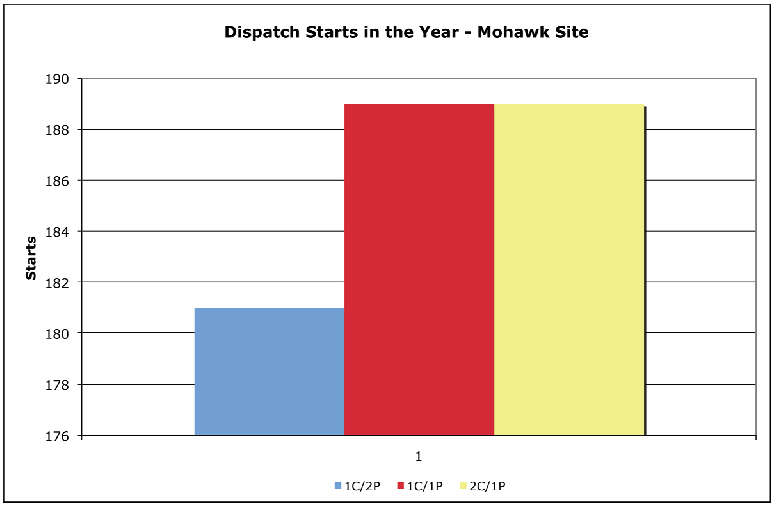


The axis "Production Hours" refers to the value derived from the n<sup>th</sup> running hour for each start. Value is summed across the year for each n<sup>th</sup> hour of run time in a specific day.

The tail in value after the first few hours of production also suggests that if a mini-CAES facility was constructed at this location, spread energy considerations alone would justify a very limited storage quantity, perhaps two hours judging by the break point, which is closer to an optimum design for a mini-CAES facility. On the other hand, the value of the spread energy peak at this location is limited, so that even a more optimum design would not be attractive.

The equipment starts do not decline as significantly as the value from the duration of run times. The equipment starts frequently but is often run for only a short period.

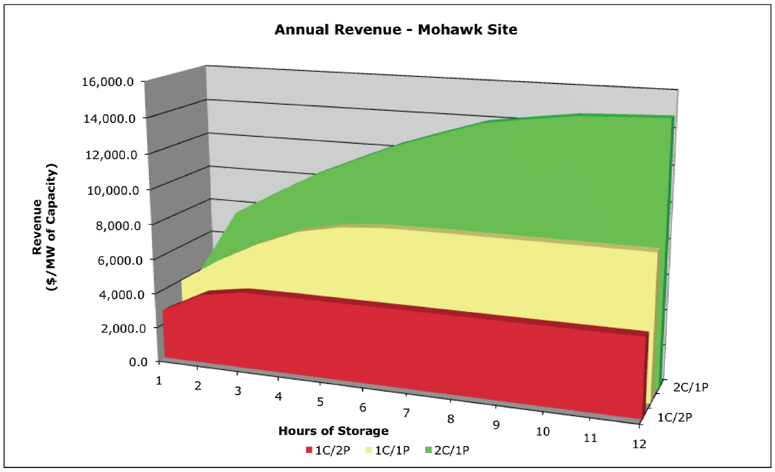
Figure 10: Starts: Mohawk



The scenario can be portrayed in terms of the cumulative annual revenue for a facility, as shown in the following figure.

For clarity, the units are correct as written, $/annum. The value of a MW of generation capacity recovers a maximum of less than $16,000/MW/yr, net of fuel and other operating costs. For this facility, that is annual revenue of about $160,000 for this project.

Figure 11: Annual Revenue: Mohawk

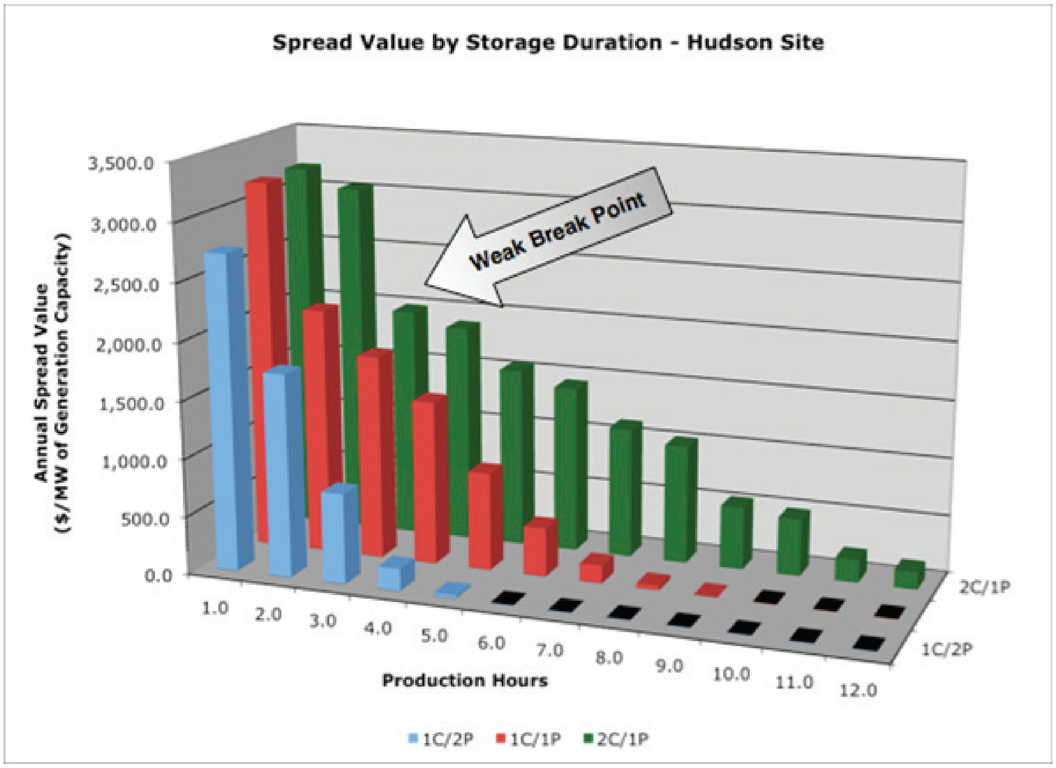


The shortfall in value is extreme. The cost of the facility at an upstate location is estimated to be either $21.3 million if the estimate for lower boundary is used or $43.2 million for an estimated installation. This implies an annual net contribution to capital of $2.5 – 5 million is required, assuming a weighted average cost of capital of 11%, or roughly 15-30 times the estimated value at this location.

Further, at this location it is not likely that (1) a transmission or distribution upgrade would be deferred by this capacity, (2) the capacity payments would not be very significant, and (3) the dispatch costs were largely being negated by changing dispatch rules, so there was no additional value contribution.

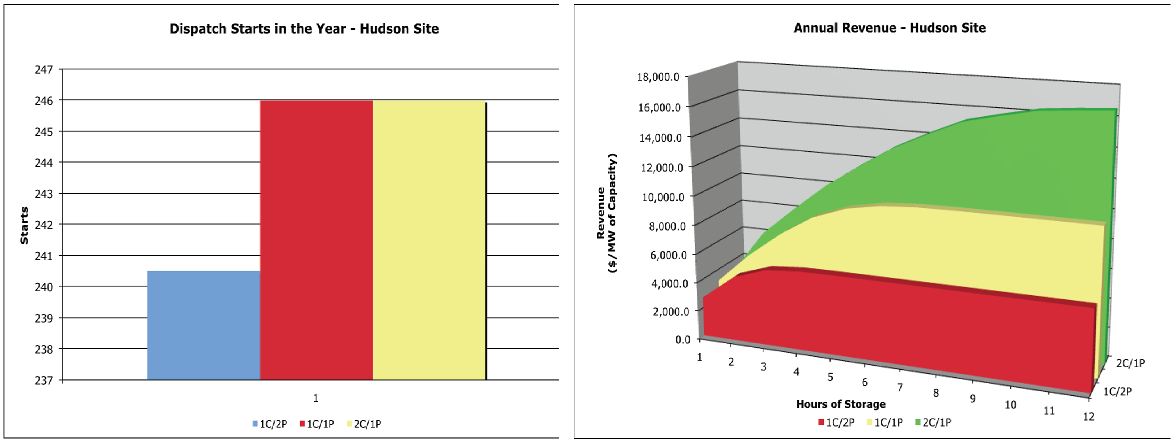
## 5.2 Scenario 2: Upstate New York – Hudson

Figure 12: Spread Value: Hudson



The analysis of the Hudson site is reduced to the same issues found at the Mohawk site, however, the energy values that resulted were different in minor ways, as shown in the above and the next set of figures.

Figure 13: Starts and Annual Revenue: Hudson



The slight increase in value is not material.

This figure points out that the amount of storage may or may not be optimized at the value break point. Since the additional hours have a reasonable amount of value, compared to the "peak," storage optimization calculations would be needed if any scenario was close to returning economic value.

## 5.3 Scenario 3: Upstate New York - West

The value at this location was broadly comparable to that of the other upstate locations, providing no opportunity for a viable facility.

Figure 14: Spread Value, Starts, and Annual Revenue West

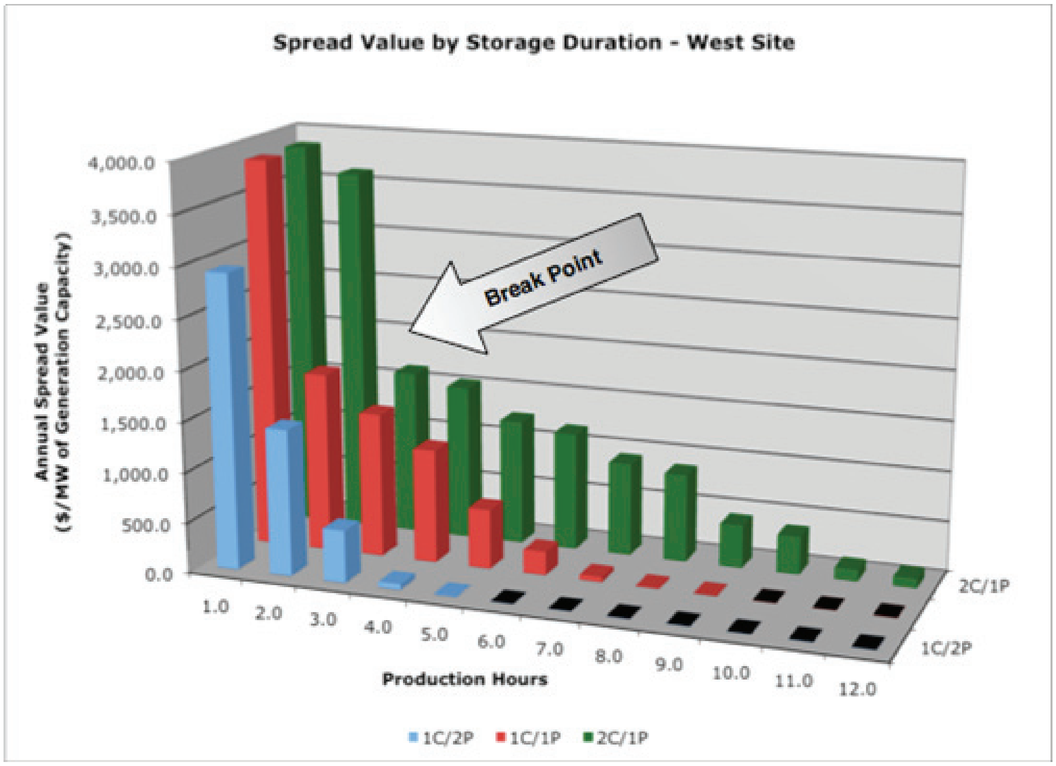
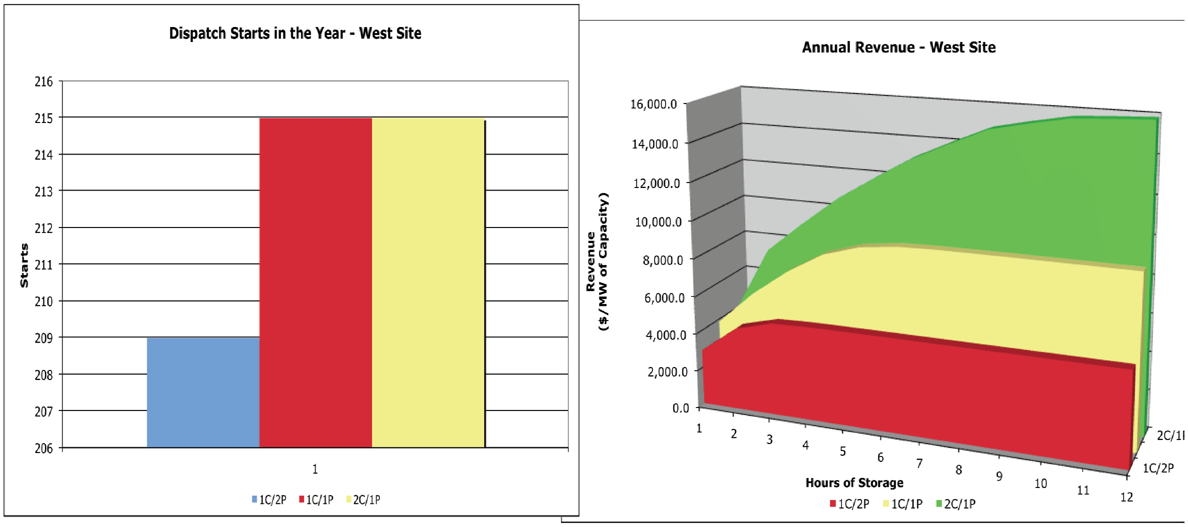


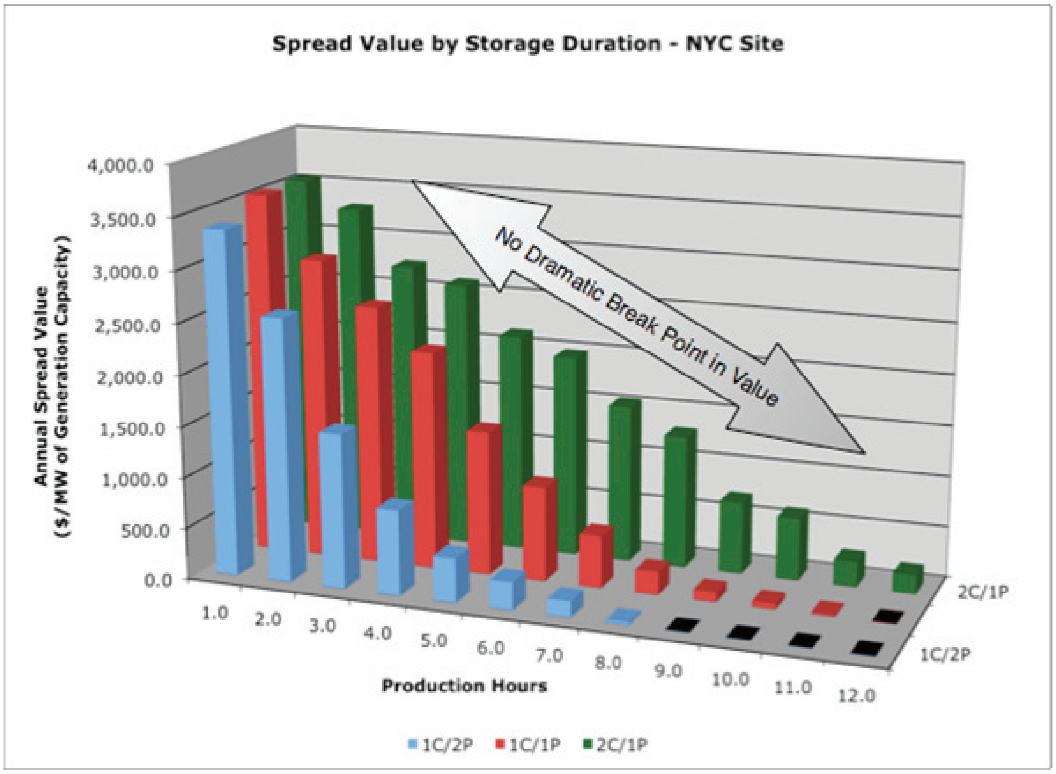
Figure 14: Starts and Annual Revenue:  West



## 5.4 Scenario 4: Metropolitan New York City

The New York City area has a higher spread value profile, but only by approximately 25%.  It is still not nearly enough to approach a viable project, especially with the additional costs associated with New York City construction.  The primary incremental value comes from improving upon the transportation constraints by purchasing power from a wind project at an upstate location and moving it into the city during off-peak hours.  Then when the plant runs during peak hours, it is providing valuable in-city generation.

Figure 15: New York City: Spread Value



The value profile contrasts with the previous scenarios. This unit shows more value in the later hours and no break point. Also, we see value for about 250 starts per year, instead of the prior levels of about 180, 215, and 245. The total value of the unit would exceed $21,000/MW/yr, plus capacity value of perhaps $20-60,000/MW/yr.

The capacity value estimated during the study period was $18,000/MW/yr and this is supported by actual 2008 ICap values listed in March, 2008, on the NYISO website, of $1,910/MW-mo and 5,320/MW-mo, depending upon the specific location. In theory the project can deliver additional fast response ICap during the compression hours of 12 AM to 5 AM, and this was cited in the project interim mini-paper.[18] However, it was later recognized that since this capacity is usually only available during the off-peak hours and it is only available when the compression cycle is running, which should not occur during peak hours, that it has little or no intrinsic value at most locations, including New York City. Since the study, the "on-island" capacity requirement was significantly reduced by the NYISO and the ICAP is only sold on a monthly basis; therefore off-peak high response capacity has no monetary value in this market.

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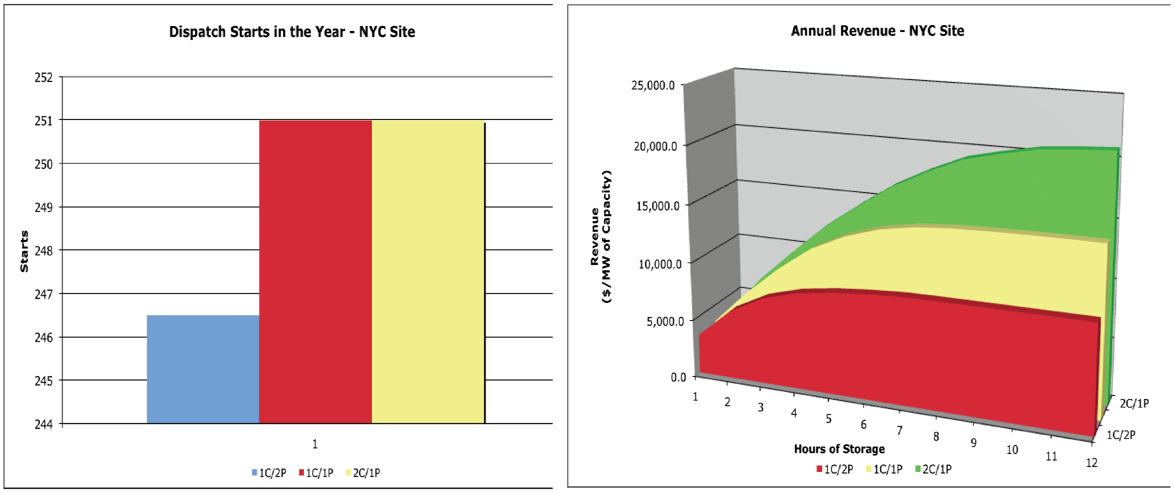
[18] Mini-Compressed Air Energy Storage for Transmission Congestion Relief and Wind Shaping Applications (Prepared for New York State Energy Research and Development Authority), presented to EESAT 2005 Electrical Energy Storage Applications and Technologies.

Figure 16: New York City: Starts and Annual Revenue



## 5.5 Scenario 5: Location Long Island

The Long Island area has a higher value profile, with annual revenue of about $60,000 and capacity revenue that might approach that value. However, it is still not nearly enough to approach a viable project, especially with the additional costs associated with New York City and Long Island construction.

Figure 17: Long Island: Spread Value

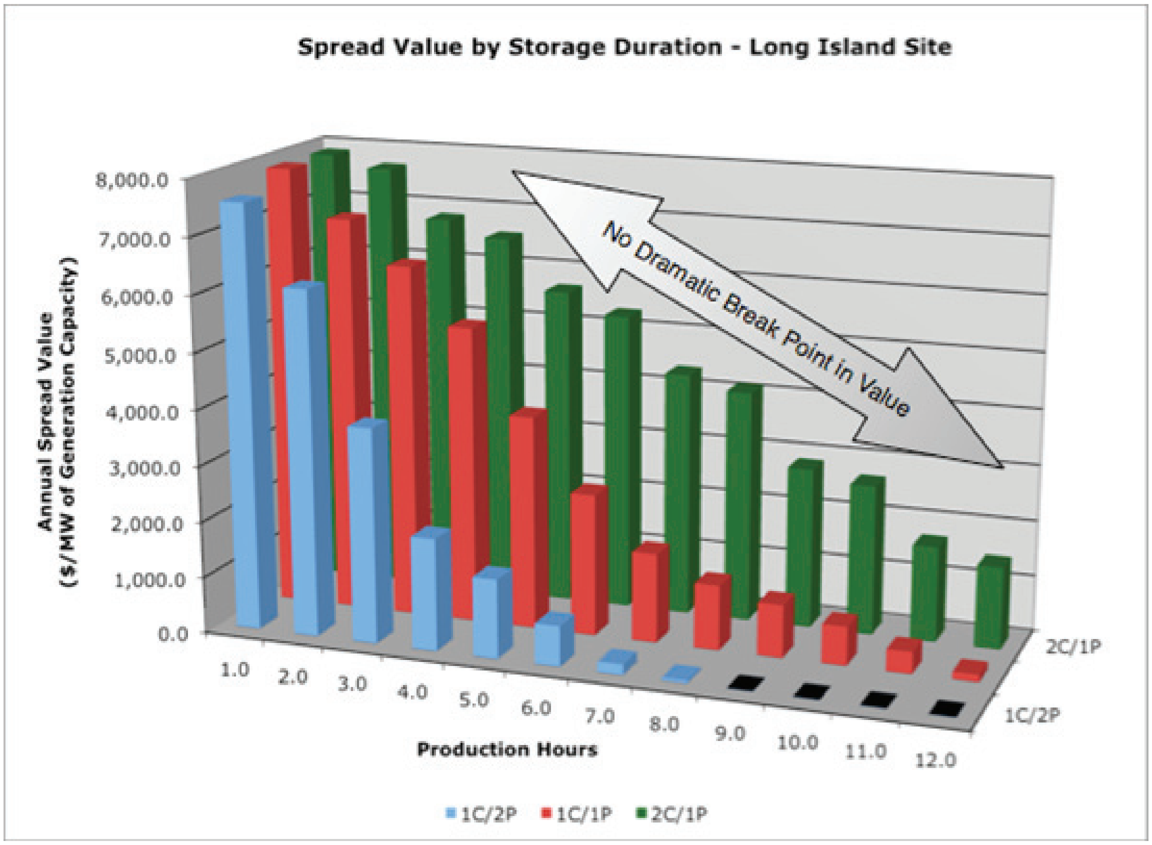
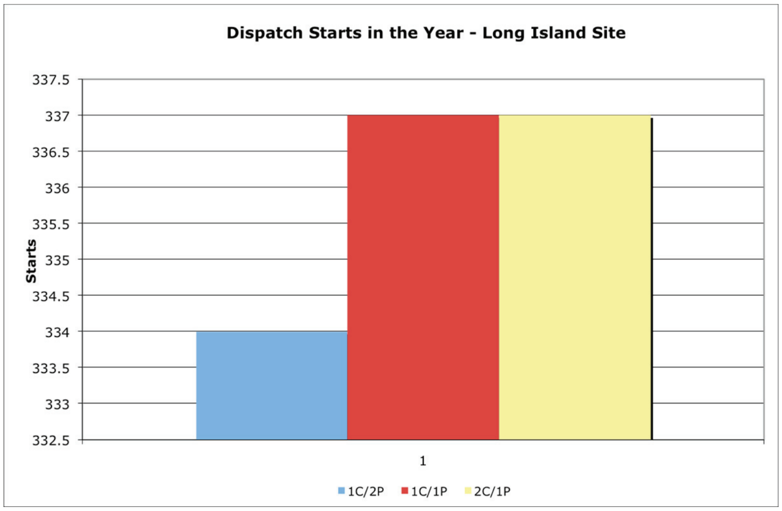


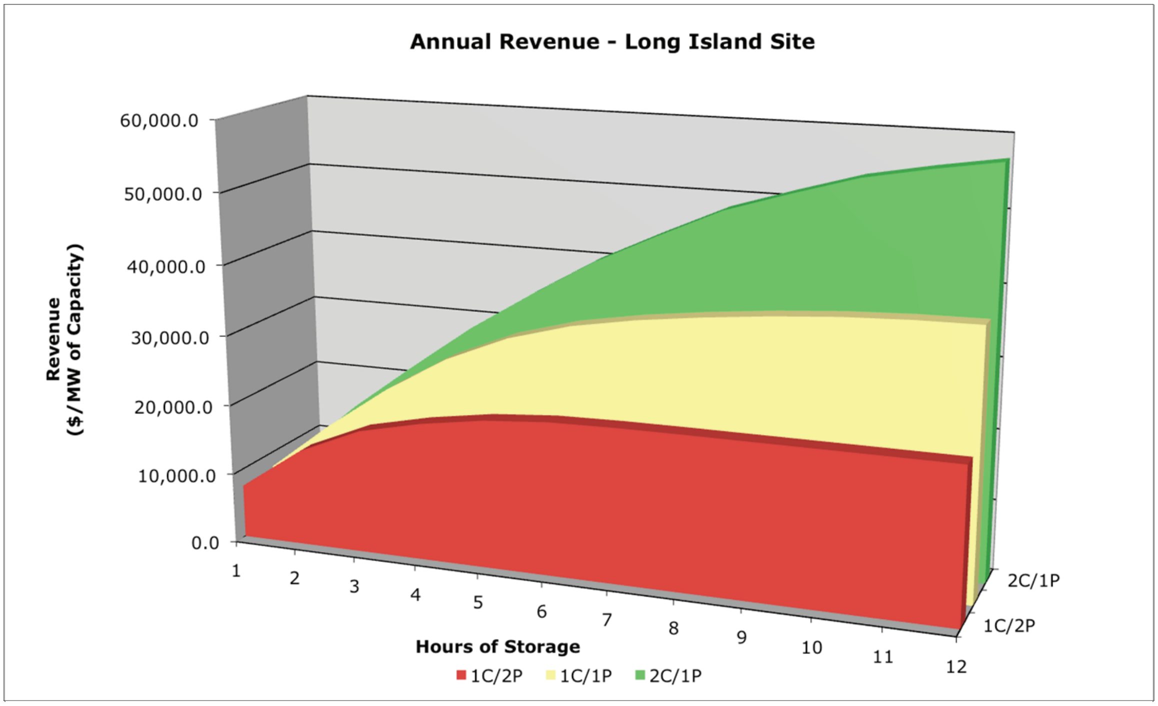
Figure 18: Long Island: Starts



The Long Island profile is very similar to New York. It has other potential advantages because the construction costs may not be quite as extreme as in the city, and there is the potential for wind projects on the island.

Long Island shows the highest number of starts, with 337/year finding value.

Figure 19: Long Island: Annual Revenue



The increased value for this location, although four times greater than the upstate locations, is not significant compared to the capital cost and this location would require significant changing circumstances to make a project viable.

One example of such a change could be the construction of a large transmission or distribution upgrade on Long Island. Perhaps a mini-CAES project could be constructed in conjunction with such a project and defer the need for transmission or distribution expansion for a couple of years. Therefore we calculated the theoretical additional value for three totally arbitrary transmission or distribution projects.

### 5.5.1 Hypothetical Deferred Transmission or Distribution Project

The following calculations follow the model described in “Valuing DG as a Distribution Alternative: Analyzing costs & benefits for multiple stakeholders; examples from SCE sample projects”, Prepared for E2I by Snuller Price, Partner Energy & Environmental Economics, Inc. (E3), draft 7-8-04. Rather than looking at the present value of the rate recovery stream, we consider annual weighted average cost of capital for the deferred construction project. If a large expensive distribution or transmission project can be deferred for perhaps two years by the presence of mini-CAES, then the saving of the cost of capital is a benefit that can be added to the other benefits of the mini-CAES project. It is feasible to create value this way because the addition of large projects is variable, while the growth in load is gradual. Each year the load may grow perhaps 2% per year. If a small distributed mini-CAES project can satisfy two or three years of growth, then the large project may be deferred by this much smaller expenditure. The basic assumptions are:

- System load growth is 2% per year.
- Target a 2-year deferral of transmission and distribution.
- Weighted average cost of capital of 11%.

The total size of the project that could be deferred is equal to two years of growth. Therefore a 10.5 MW project can satisfy growth of 10.5/2 =5.25 MW per year. If that market growth is averaging 2% per year, then 5.25MW/yr / 2% annual growth totals a market size of about 263 MW.

Assume that a transmission / distribution project being deferred that under a rule of thumb might cost about $1/kW/mile in upstate New York will cost about $1.5/kW/mile on Long Island, with transformation in the order of $1MM. All these costs are rules of thumb. The project might therefore cost as follows:

Table 10: Project Deferment Benefit Scenarios

| Distance (miles) | 5 | 10 | 100 |
|---|---|---|---|
| Capital Cost ($MM) | 3 | 5 | 40 |
| 2 yr Deferral Value ($MM) | 0.6 | 1.0 | 8.8 |

That suggests that while deferral of expansion is a legitimate value, the value is not overwhelming. The annual cost of capital requirement for a mini-CAES project is $2.5 – 5 MM, and it will receive a one-time contribution to value of about $1 – 10 MM.

As a practical matter, it is unlikely for a utility to choose mini-CAES, a new technology, to defer such a project, and it will be very difficult for another party to monetize the benefit.

This deferment benefit does bring up the abstract possibility of one way to make a viable mini-CAES project. If a mini-CAES allows a developer to accelerate the construction date of their wind generation or other commercial project then a substantial benefit is possible. The developer’s project need not be generation related. It could be a power consuming facility that requires high quality reliable power.

### 5.5.2 System Support Services

Late in the study period we received advice from Consolidated Edison that System Restoration in the CECONY service area is a challenge because of the large networks. The mini-CAES would provide very minimal benefits in preventing urban blackouts, system restoration, and operating reserves.

As a consequence, we found no value for any system support services, despite the theoretical ability of the units to deliver such. This was in direct contrast to the in-progress paper, which scaled theoretical values to the smaller project. The mini-CAES projects deliver extremely fast response, long hours of synchronized condensing, black start, and can deliver direct VAR control. Initially the thought process emphasized the quality of the services and the economy and durability of the equipment while providing such services, but the Con Edison position about the importance of scale is a compelling point of view, which the study accepts.

### 5.5.3 Sensitivity: Energy Ratio

There is one more element of the design that was disappointing to the NYSERDA project team; the energy ratio. With an energy ratio of just 0.88, the amount of energy that is effectively stored by the mini-CAES project is quite low.

An arbitrary sensitivity based on the energy ratio was considered using the highest worth location, Long Island. The value of 0.51 was chosen to match the lowest reported energy ratio found (noted in Table 4-4, page 4-8, of the EPRI Study). The EPRI Study found this to be the best energy ratio for a particular design of 15.9 MW steam injected power plant (STIG).

The NYSERDA plant design is not the same as this design, and significant changes would be required. This is an arbitrary comparison to test the boundary conditions and assumes that the only change in the power plant is that of the energy ratio. Power output is still 10.5 MW, capital cost does not change, and operating cost does not change (ignoring the additional water consumption, among other issues).

This sensitivity finds that each MW would develop about $126,000 of value with notionally $1.323 million of total project spread energy value annually, compared to the prior spread value of $599,000. This, combined with the capacity value, improves the overall Value Realized to Value Requirement Ratio to 29% of the economic requirement.

($1,323k spread value + $455k capacity value) /( $6,098k project cost of capital)[19] = 29%

## 5.6 Value Summary

The economic analysis applied the variable costs to find the plant run times and the value from those running times. Appropriate matches of low cost charging power consumption and high value generation in a day were dispatched and the value totaled, net of variable costs. It was assumed that dispatch was made perfectly, always purchasing the lowest cost power and selling at the highest hourly prices. Annual savings from this dispatch was compared to the capital requirements of the investment in a simple test to consider the worth of the projects.

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[19] Table 11, following.

The plant can capture spread value and capacity payments, which must be sufficient to recover fixed operations costs and return on capital. Since the realized value was so deficient, the comparison was not carried into a multi-year proforma analysis.

The results are summarized below for the highest valued upstate location, Hudson, and the highest valued downstate location, Long Island.

Table 11: Value Summary

| | Hudson Costs | | Long Island Costs | |
|---|---|---|---|---|
| | ($k) | ($k/yr) | ($k) | ($k/yr) |
| Base Capital | 30,240 | 3,326 | 42,630 | 4,689 |
| Indirect Capital | 12,810 | 1,409 | 12,810 | 1,409 |
| | | | | |
| Total Costs | 43,050 | 4,736 | 55,440 | 6,098 |
| | | | | |
| | **Hudson Value** | | **Long Island Value** | |
| Spread Energy Value | | 173 | | 599 |
| Capacity (ICAP) | | 455 | | 455 |
| Dispatch | | 0 | | 0 |
| Total Value | | 629 | | 1,054 |
| | | | | |
| **Value Realized /<br>Value Requirement: total capital** | | **13%** | | **17%** |
| **Value Realized /<br>Value Requirement: 50% cost** | | **26%** | | **34%** |

Even the combination of lower than estimated capital costs, most favorable location, and the higher value through an arbitrarily and extremely improved energy ratio do not bring the project a reasonable economic return. If we test the boundary scenarios together, including 50% capital cost, the highest revenue scenario (Long Island), and extremely high energy ratio (0.51), we find just 58% of the required value has been met. ((1,323 + 455) / (6,098/2) = 58%)

# 6 CONCLUSIONS AND RECOMMENDATIONS

The mini-CAES unit does not appear to be viable in this assessment, even when comparing the boundary case scenarios for possible lower costs and higher efficiency.

Several points of value that were anticipated at the beginning of the study proved to be illusive either due to changing circumstances or due to the small scale of each facility. Specifically, economics from stabilizing wind variability to provide a dispatched product were reduced by changes to the dispatch penalty provisions. The ancillary services values exist, but could not be monetized at this time because the utility does not find the small scale to be a useful contribution to the system.

<u>Recommendation 1</u>: We recommend that a party looking to find a commercial application first find a setting where storage is significantly more valuable than a generation unit and where that value can be realized with some form of available contract.

The support of the local utility would be instrumental in monetizing the value that accrues to the grid, but such support is not likely in a large urban location. We suppose that there may be commercial customers suited to these facilities, but have not identified any. In addition to the difficulty of identifying a situation where this could bring sufficient value to justify the expense, we wonder whether this would ever prove to be the most economic solution.

<u>Recommendation 2</u>: We recommend the next project begin with a better literature search to build on the work that has been done before. Our search was too cursory and was limited to the Web and a small number of interviews. It failed to turn up the “EPRI Project” until late in the process, which could have stimulated ideas for the better use of capital.

<u>Recommendation 3</u>: If a party did wish to investigate a mini-CAES solution, which we are not recommending, we do suggest a different approach than utilized for this project.

Start by identifying value in a specific location and focus on the attributes to maximize that value. Then spend time conceptualizing the ways to achieve the desired energy ratio and power before choosing equipment and design.

Deferring spending on engineering until the value has been defined <u>and</u> confirmed may prevent the difficulties encountered here where theoretical value was found impractical in the current market. Also, developing the project in series reduces the development costs that are incurred “at risk” in the early stages. In contrast, this study began with the expectation that something approaching a valuable application was feasible, and therefore, proceeded with engineering and economic assessments in parallel. During the early stages of the project, sufficient value appeared within reach from theoretical premise of the function of the equipment, but in fact the value proved to be not commercially viable.

Recommendation 4: If a project reaches the stage when additional engineering is undertaken, the facility design should focus on low construction cost modular or trailer mounted designs and on the energy ratio.

The following comments consider the uncertainty around a couple of key estimates:

- Value may come from identifying a service where the bulk storage is appreciated. That might be found in some fairly large commercial setting, such as a high security server hosting business at a remote location, if it valued the innate flexibility of the technology. There is upside potential in the uncertainty of value.
- Spread value will change from time to time as perspectives of the grid change, but it is not likely to become a dominant driver of value. The value uncertainty appears to be neutral for spread value.
- Energy storage is very inefficient in the chosen design, with an energy ratio of just 0.88. There is upside uncertainty around the possibility for a new design.
- Storage costs benefit from extensive engineering by the Enersea Company and favorable assumptions for code approval. There is downside uncertainty in the storage design due to pressure on steel prices and the possibility that an ASME code design may be required.
- Engineering and assembly costs were estimated on an all inclusive basis. The uncertainty around the cost estimates is weighted toward designed savings in cost.

Although there are significant improvements possible, the authors cannot recommend any further work without a breakthrough change in thought process. Even when running “boundary” case sensitivities for cost and energy ratios, no scenario suggested that even 60% of the required value could be recovered. Only the identification of an additional form of or location for value will make a project viable.

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# MINI-COMPRESSED AIR ENERGY STORAGE FOR TRANSMISSION CONGESTION RELIEF AND WIND SHAPING APPLICATIONS

FINAL REPORT 08-05

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