Energy Storage for Grid Connected Wind Generation Applications

EPRI-DOE Handbook Supplement

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PRODUCT DESCRIPTION

To date, the use of energy storage systems to optimize wind power generation has been limited to small, off-grid rural or village power applications plus a few technology demonstration-scale battery storage projects for grid connected applications. However, recent developments in advanced energy storage technologies and other technical, economic, and social factors suggest a promising future for such energy storage applications. This Handbook Supplement provides an objective information resource on the leading, near-term energy storage systems and their costs and benefits for a range of leading grid connected wind power applications.

Results & Findings

The Handbook Supplement addresses the benefit-cost assessment of energy storage to optimize wind power resources connected to the grid. As such, it provides a guide for utilities and/or wind power generators considering leading energy storage systems for representative applications in curtailment mitigation, time shift of firmed and shaped wind generation from night to day, forecast hedging, grid frequency support and fluctuation suppression. The Handbook Supplement provides a structured, easy-to-use resource for formulating comparative technology/application assessments and quantifying costs and benefits for such single function applications as well as for select combined wind power related plus other grid support functions. It parallels the structure of the earlier Energy Storage Handbook for T&D Applications (EPRI report 1001834, hereinafter “Handbook”) and references the Handbook as the source of technical and economic information on then available energy storage technologies: lead-acid, nickel electrode, and sodium-sulfur modular batteries; zinc-bromine, vanadium redox, and sodium polysulfide-sodium bromide flow batteries; superconducting magnetic energy storage (SMES); flywheels; electrochemical capacitors; and compressed air energy storage (CAES). Each applicable technology is ranked as to suitability, and compared with other technologies, in one or more of the 9 different wind power related applications.

Challenges & Objectives

With the many challenges facing utilities and others responsible for optimally harnessing grid connected wind power, considering the broadest range of technically and economically viable solutions is more important than ever. Electricity storage is increasingly one of the potential solutions for certain applications and circumstances. Two concurrent reports from EPRI’s Renewable Energy Program (EPRI reports 1008388 and 1008852) respectively address the full range of such technology solutions and the best practices of energy storage applied to grid connected wind power systems.

Applications, Values & Use

The Handbook Supplement provides a structured economic evaluation framework to utilities as well as wind power generators for selecting and evaluating candidate energy storage options for grid connected wind power related applications and formulating comparative assessments. Technology functionality, and benefit-cost information in the Handbook Supplement will help users evaluate the viability of the technology for specific applications and help establish a basis for more detailed, site-specific assessments by utilities, wind power generators and energy storage system suppliers working together to optimize the overall grid and the wind power resources.

EPRI Perspective

EPRI undertook the development of the Energy Storage Handbook in partnership with the Department of Energy's Energy Storage Program who supported the preparation of a dedicated chapter on the National Perspective on Electricity Storage Benefits. As a further extension of this partnership, this Handbook Supplement has been cofunded by EPRI and DOE. The Handbook represented the first and only nationally available and broad consensus based information resource of significant depth and detail on energy storage for utility T&D applications. Its usefulness and range has now been extended to grid connected wind power applications with this Supplement. As such, the two documents should greatly stimulate the consideration and deployment of electricity storage in utility operations leading to increased asset utilization, system reliability, and wind power optimization.

Approach

The project team utilized a similar pool of expertise in electricity storage technology as was done for the Handbook, as applicable for grid connected wind power applications. The team first conducted an overview of grid connected wind power throughout the world with an emphasis on energy storage applicability. It then formulated the select wind applications and duty cycles, with their respective value propositions as the basis for the benefits. Common economic and cost parameters from the Handbook were adopted in the present work. The team reviewed each energy storage technology chapter in the Handbook, addressing any major changes, and collected and assessed major hardware or wind power assessment experience, Regarding the latter, the applicability or lack thereof for wind power applications of storage and plus any new parameters required for such wind related applications were noted. The same standard assessment and comparative benefit-cost results framework from the Handbook effort was applied. However, in preparing the Supplement, the applicable content from the Handbook was referenced, but not repeated. Hence, the Supplement is not a stand-alone document.

Keywords

Wind energy integration
Energy storage
Grid frequency stability
Batteries
Flywheels
Electrochemical capacitors
Compressed air energy storage (CAES)

ABSTRACT

The use of stored energy for the optimization of grid connected wind power resources has been limited to date, primarily due to a lack of cost-effective options as well as actual field experience and comparative evaluations. Recent developments in advanced energy storage technology, including a several wind power related demonstration projects and assessments, are providing new opportunities to use energy storage to optimize grid connected wind power in curtailment mitigation; time shifting of firmed and shaped wind generation from night to day; forecast hedging; grid frequency support and fluctuation suppression applications. This Handbook Supplement assesses the potential benefits and costs of energy storage for such single and combined applications and provides a "technology-neutral," comparative framework that utilities and/or wind generators can use to formulate detailed application and site-specific assessments of specific technologies. The Handbook Supplement provides an overview of grid connected wind power with emphasis on energy storage applicability, details the current demonstration and major assessment experience with wind power, plus the costs and benefits of the leading applicable storage technologies: lead-acid, nickel-electrode, and sodium-sulfur modular batteries; zinc-bromine, vanadium redox, and polysulfide-bromide flow batteries; superconducting magnetic energy storage (SMES); flywheels; electrochemical capacitors; and compressed air energy storage (CAES). Each technology is ranked as to suitability, and compared with other technologies, in one or more of 9 different grid connected wind power related applications. The Handbook Supplement references the earlier EPRI-DOE Handbook of Energy Storage for Transmission and Distribution Applications for applicable content. Hence, the Supplement is not a stand-alone document.

ACKNOWLEDGMENTS

In December 2003, the EPRI-DOE Handbook on Energy Storage for Transmission and Distribution Applications was issued with the benefit of contributions from throughout the utility-scale energy storage community. This Handbook Supplement, as well as the original 2003 Handbook, would not have been possible without the funding and enthusiastic support of the utility members of EPRI's Program 94, Energy Storage for T&D Applications. The support of the following Program 94 members in 2004 is gratefully acknowledged:

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California Energy Commission	Hydro One Networks, Inc.
California ISO	Jacksonville Electric Authority
Central Hudson Gas & Electric Corp.	Lincoln Electric System
Dairyland Power Cooperative	New York Power Authority
East Kentucky Power Cooperative, Inc.	Omaha Public Power District
Golden Valley Electric Assn., Inc.	Public Service Electric & Gas Co.
Grant County Public Util. Dist.	Richmond Power & Light
Great River Energy	Tri-State G&T Association, Inc.

As well, the support of EPRI's Program 84, Renewable Technology Options and Green Power Marketing, which provided collaborative support to this Supplement, is acknowledged.

As with the 2003 Handbook, EPRI would like to gratefully acknowledge the cooperation and co-sponsorship of the U.S. Department of Energy through the Sandia National Laboratories for the production of the Handbook Supplement.

Throughout the course of the Handbook Supplement development, review and comment has been contributed from industry experts for select topics. In addition, several energy storage vendors have contributed directly to update the information and support the benefit – cost assessments for their respective technologies. All of these contributions are gratefully acknowledged. In particular, EPRI gratefully acknowledges the contributions of Nisha Desai of Ridge Energy Storage, including sharing of wind – energy storage assessment software, the applicability of such to CAES for site-specific wind conditions plus the review and update of CAES cost and performance parameters.

EPRI also acknowledges the continued dedicated efforts of the contractors: Harold Gotschall and Dan Mears, Technology Insights; and Haresh Kamath, EPRI PEAC Corporation.

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1 INTRODUCTION

The use of stored energy for the real time and short notice (milliseconds to a few minutes) support and optimization of the generation, transmission and distribution (G, T&D) system has been limited to date to pumped hydro systems and, in a couple of instances, lead-acid or nickel cadmium batteries, primarily due to a lack of cost-effective options. Recent commercial advancements in energy storage and power electronic technologies are providing new opportunities to use energy storage in grid stabilization, grid operation support, distribution power quality, load shifting and intermittent renewable, e.g. wind generation, applications. Such energy storage resources may derive major value based on locational conditions, as opposed to the large, central pumped hydro energy storage facilities, as well as the ability to serve multiple optimization functions to various combinations of the G, T and D utility business sectors. However, capturing the full benefits may be challenging if utility restructuring has constrained the sharing of such benefits among these sectors, which in turn constrains the deployment of such energy storage systems.

With the reality of energy storage and power electronic technology advances plus application opportunities and challenges for the utility sectors, EPRI's Energy Storage Program undertook the development of the Energy Storage Handbook for T&D Applications, which was issued in December 2003 [1] – hereinafter referenced as "Handbook." The synergism between the goals of the Handbook and those of the DOE Energy Storage Program led to DOE's co-sponsorship, with the preparation of the National Perspective on Electricity Storage Benefits chapter therein. As such, the Handbook assesses the potential benefits and costs of energy storage on the national and corporate level and provides a "technology-neutral," comparative framework that utilities and others can use to evaluate representative, leading applications with the leading utility-scale energy storage systems as a screening step in deciding whether to engage a detailed, site-specific project assessment with the respective vendors. The Handbook represents the first and only nationally available and broad consensus-based information resource of significant depth and detail on energy storage for utility T&D applications.

Purpose of Supplement

In 2004, EPRI and DOE have co-sponsored this "Supplement" to the Handbook to address the use of energy storage to optimize grid connected wind generation resources. With mandated renewable portfolio standards calling for more renewable generation and the steady advances in wind power systems and economics bolstered by the continued government subsidies plus public demand for "green power", wind generation has become the fastest growing generation resource in the U.S. and many other countries. However, as the fraction of wind power rating becomes significant relative to the load and the capacity of the grid, there are increasing issues due to the wind's inherent intermittency associated with grid stability and added costs associated with increased demands for regulation control, spinning reserve and/or transmission capacity. Energy storage is one option to respond to such issues plus offers the capability to firm and shape the wind generation resources for further economic optimization. Such is the scope of this Supplement. Altogether, the combined Handbook and Supplement efforts should stimulate the consideration and deployment of energy storage in utility operations leading to reduced cost of service through increased asset utilization, system reliability, and wind power optimization.

In parallel, EPRI'S Renewable Energy Program is developing a report titled "Best Practices for Energy Storage Applications to Wind Power [2]. This report identifies the best practices from specific hardware demonstration projects as well as major assessments and serves as the primary resource from which the summary level of such experience is presented herein within the respective energy storage technology chapters. EPRI's Renewable Energy Program is also developing a related report titled "Engineering and Economic Evaluation of Wind Turbine Design Innovations for Smoothing Power Fluctuations" [3]. This reports addresses energy storage as one of several technology solutions for smoothing wind power fluctuations. Both reports are scheduled for issuance in March 2005.

Scope of the Supplement

The scope of this Supplement parallels, but does not repeat the Handbook scope and content to the extent practicable for ease of near-term use together as well as the expected future integration of the Supplement into an updated and expanded Handbook. Hence the Supplement is <u>not</u> a stand-alone document.

As before, the Supplement scope is both broad and specific. The broad scope follows in Chapter 2 with an overview of grid connected wind power resources with emphasis on potential energy storage applicability. The focus throughout is on high voltage (>13kV) and high power (>100MW) grids with the Big Island of Hawaii, which is a current case study of interest, serving as the low end. Hence, small island grids and remote off-grid village power applications of energy storage with wind power are not addressed herein. Such applications typically adapt hybrid combinations of diesel gensets and/or smaller scale energy storage systems.

The remainder of the Supplement contains the parallel and additional specifics needed to assess energy storage applications with grid connected wind power resources. Chapters 3, 4 and 5, respectively, describe the specific wind power applications, the economic benefit bases of such, and any new common cost elements for evaluation from the overall integrated utility perspective, or alternatively, from a wind power generator perspective with the ability to accrue the benefits of the T and/or D utility.

In Chapter 3, the specific grid connected wind power applications are described. Single function applications include: Transmission Curtailment (TC), Time Shift (TS) of wind generation from night to day, Forecast Hedging (FH), Grid Frequency Support (GFX) and Fluctuation Stabilization (FS). These individual applications are described with emphasis on the grid phenomena being addressed and the role of stored energy to support the grid and/or the wind generation. Top-level requirements (e.g., duty cycles) and reference values used in benefit-cost assessments are identified. In addition to the five single function applications, four combined function applications are also characterized (e.g., combined FS, LS and Regulation Control (RC) – the latter being a Grid Operation Support function from the Handbook. As before, the economics of most energy storage systems are significantly more attractive for multi function applications, albeit with potential institutional issues of sharing such benefits among the G, T and/or D sectors of the utility industry, as noted above. The energy storage systems suitable to address the resulting set of nine representative opportunity applications are identified.

In Chapter 4, the bases and approach used in quantifying the benefits associated with each application are presented. Benefits are treated in two categories: those associated with representative electricity market rates (e.g., trading values for firm and nonfirm electricity energy, capacity credit for firm wind resources, penalties for wind generation forecast deficiencies, ancillary services values, etc.) and those related to the avoided cost of alternative solutions (e.g., transmission upgrades, regulation and spinning reserve resources, peaking generation, competing technology, etc.). As with the Handbook, the quantification of market-based benefits is obtained from a representative single value, while the value of avoided costs is represented over a range (e.g., the net capitalized costs of alternative technology solutions). It is intended to allow the reader to conduct an initial screening of options by extrapolating the results of economic analyses reported herein to their respective project specific values and options.

Chapter 5 references the Handbook for the costs that are typically common to the various energy storage systems, such as the power conversion system, the balance of plant, grid interface and routine property taxes and insurance. Such common costs from the Handbook are fully applicable to the wind power applications.

Chapters 6 through 15 then follow for the respective energy storage systems with an update of major changes for the respective energy storage systems since the Handbook, a summary of any wind power related demonstration projects and/or major application assessments, plus any supplemental technical parameters related to the wind applications in Chapter 3, technology-specific costs and the resultant benefits assessment results, plus pertinent references.

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2. Best Practices for Energy Storage Applications to Wind Power, EPRI, Palo Alto, CA: scheduled for March 2005. 1008388.

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2
OVERVIEW OF GRID CONNECTED WIND POWER

Background

Wind power is currently the fastest growing source of generation in the U.S. and many other countries. This has resulted from the combination of several interrelated factors, including:

- Strong political support for renewable energy per se, which is due to the attendant environmental advantages, associated the absence of greenhouse gas emissions, as well as National energy security advantages. For wind power, NIMBY based aesthetics has become an offset environmental issue in some regions, and likely to increase with further rapid expansions. In any event, Federal and State government subsidies have continued that typically offset the initial costs, provide price support or provide a credit for wind generation production. In the U.S., the Federal Production Tax Credit (PTC) currently provides wind generators an inflation adjusted credit of 18$/MWh for the first 10 years of operation. Thus far, the Federal government has failed to establish a long-term consistent policy for wind energy subsidy and incentive, choosing instead to renew the PTC for 1 to 3 years. The occasions that such PTC support may terminate by year-end has created a rush within the wind industry to implement new projects. Likewise, the occasions of such support being suspended during Congressional deliberations for continuance of the PTC support has stalled the development of new wind projects.
- Rate payer selected willingness to pay a premium for "green power" as a personal means to advance renewable energy. In the U.S. as of the end of 2003, more than 500 utilities, including cooperatives, in 34 States offer green pricing programs. Altogether, more than 265,000 customers are participating in utility green pricing programs, including 6,500 nonresidential customers. While still a tiny fraction of the total market, the energy delivered to customers through green pricing programs increased 16% in 2003 and since 1999 has increased fourfold. As a result, about 520 MW_{ac} of new renewable generation has been built of which about 82% is wind. The green price premiums range from 0.6 cents/kWh to as much as 17.6 cents/kWh, with an average of 2.0 cents/kWh [1].
- Improved wind power system economics, due in large part to ever increasing power ratings, larger manufacturing operations and improved performance capabilities of the wind turbine systems. Included in the latter are "soft-handshake" inverter –connected systems which mitigate the voltage and frequency instability effects of fluctuations plus low-wind generating technology which allow cost effective installations in low-wind areas. Such improved economics have led many utilities to view wind generation as a hedge against the increasing volatility in natural gas prices.

- As a result of all the above, governments at all levels are increasingly mandating Renewable Portfolio Standards (RPS) that require (or target) the distribution utilities to achieve certain fractions of their delivered energy with renewable energy resources. In the U.S., about 20 States have in-place or are actively considering such RPS, which vary considerably with the more aggressive States requiring up to 20% by the year 2020. New York has a 25% RPS requirement by 2012, but already obtains 17% of its generation from hydro plants [2]. Similar Corporate mandates are also being imposed.

Wind power resources inherently fluctuate and even with large wind farms that provide some self compensation of such variability by local spatial variations in the wind, the day-to-day variations can range from zero (wind below turbine cutoff speed) to near full rated output. A yearly average capacity factor for modern wind turbine farms is in the range of 30 to 40%. However, diurnal and seasonal variations may differ by a factor of 2 or more. The annual power output of a typical wind farm in the upper Midwest of the U.S. is presented in Figure 2-1. This profile is based on actual wind power data collected by NREL and illustrates the variability to be managed, effectively as a negative load, on the grid. Actually, the power data in the figure are averaged over a day time interval which serves to dampen the fluctuation intensity.

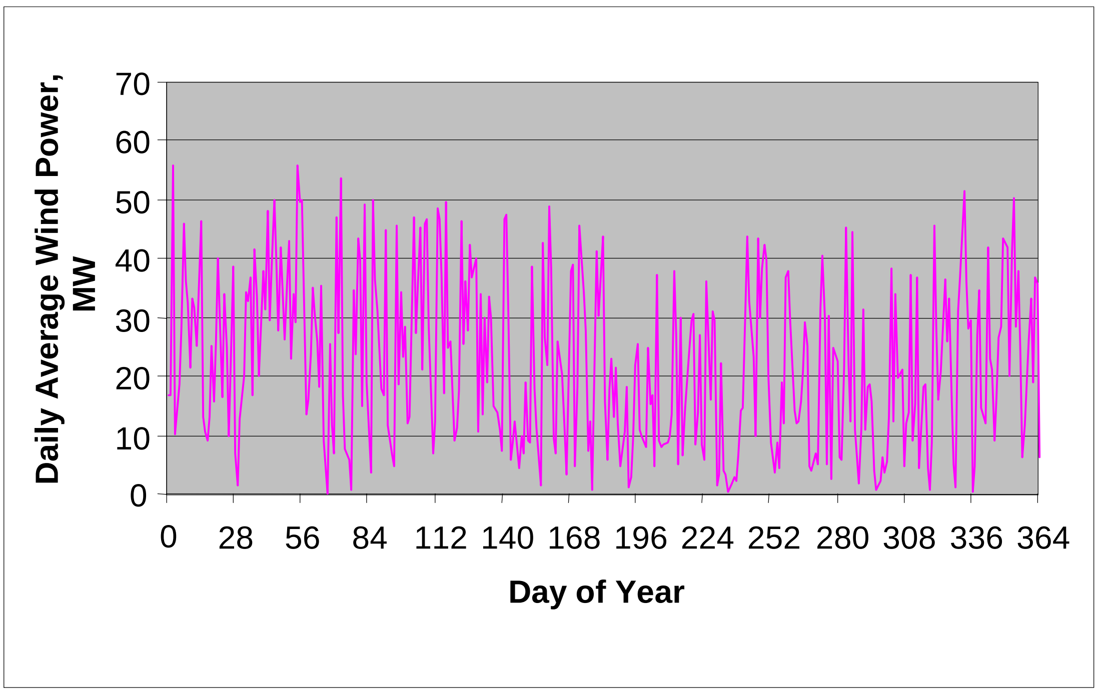

Figure 2-1
Typical Wind Power Resource (Courtesy of NREL)

Wind power has been largely deployed by third party generators. Initially, most of the contracts have been based on a constant energy price which may reflect the lowest price bid or the utility's avoided energy costs, plus the price is typically paid whether the grid is able to deliver the energy or not. Increasingly, wind generators are selling to open markets with daily and hourly bid options that apply wind forecasting models as the basis for their bids.

The status of wind power deployment and the recent rapid growth around the world is illustrated in Figure 2-2 [3]. The recent exponential growth for the world as a whole and Germany in particular is dramatic. Table 2-1 summarizes the peak load, the current installed wind power capacity and the resulting penetration percent [3]. Note that while the penetration percent for Denmark is noted to be 82%, the situation is bit unique in that their grid connections with Nordpool and Germany provide the effective transmission capacity to absorb their high wind penetration percent without undue cost penalties. The resultant percent of wind energy delivered in Denmark is about 21% [4].

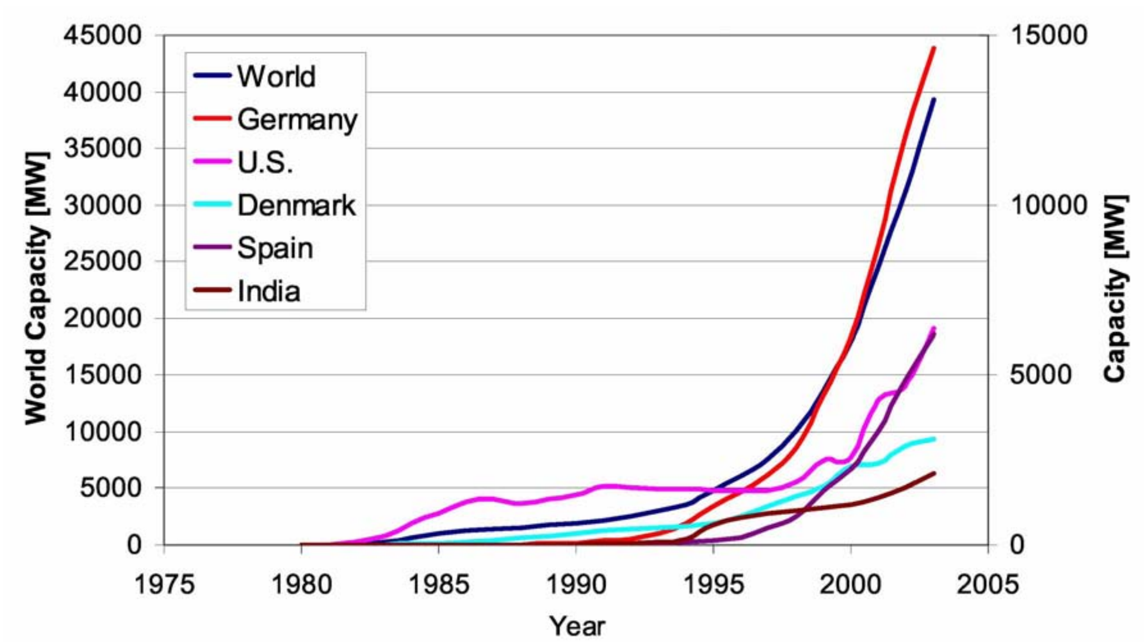

Figure 2-2
Wind Power Growth for the World and Select Countries (Courtesy of KEMA)

Table 2-1
Wind Penetration – Wind Rated Capacity/Peak Load (Courtesy of KEMA)

Region	Peak load [MW]	Installed Wind [MW]	Penetration
Denmark	3800	3100	82%
Germany	77000	14600	19%
Spain	36000	6200	17%
The Netherlands	14000	1000	7%
Continental USA	808000	6400	1%
Texas	63000	1900	3%
New Mexico	1500	200	13%

Integrating Wind Power with the Electric Grid and Energy Storage Opportunities

Other than for special circumstances such as Denmark, the integration of wind power resources is not a significant issue as long as the penetration rates are small, typically <10%, assuming there are no grid capacity or otherwise stability constraints. As wind power becomes a significant fraction, typically >20%, of the load, added regulation and spinning reserve resources are required for adequate grid stability control. The costs of such have been the subject of much study, particularly in the U.S. and Europe [5, 6, 7]. Reference 5 summarizes five other analytic and case specific studies in the U.S. where the level of wind penetration ranged up to 22.5%. The cost impact ($/MWh) on wind generation was relatively small – with a maximum addition of 5.5$/MWh. At present, such added costs are absorbed by the grid operator and passed on to the rate payers as a further effective subsidy to wind power. Alternatively, the grid operator may mandate that the wind generator meet certain stability requirements as a condition for grid access. In either case, such costs will increase with wind penetration and represent an opportunity for energy storage systems that can be applied directly to the wind resource or more optimally to the grid, that integrates the negative wind load with the normal varying load, to provide all or some portion of the additional regulation control and spinning reserves attributed to the wind.

Increasing wind generation may also reduce the regulation capacity of the control area as a result of the increasing wind generation necessarily reducing the contribution from other generation, if the load remains constant [2]. The displaced generation will likely be the marginal generation that is least economic to run, as opposed to the lowest cost base-load generation. This displaced marginal generation is also the generation that has maneuvering capability available and often supplies regulation capacity to the grid.

Several studies [4] indicate that the hourly output from a large, distributed wind farm will rarely change more than 20% of the rated capacity of the wind farm. This serves as a first order guide for sizing energy storage systems for the purpose of supporting significant penetrations of wind power on the grid, whether at the transmission or distribution level. For the latter, energy storage may allow wind power access to the distribution system that would offset the need for an otherwise transmission line extension to the wind farm and the attendant costs.

By its nature, the amount of grid capacity to accommodate the full wind power resource is based on the rated capacity, whereas the average capacity is typically 30 to 40%. Hence, relative to other base generation options, wind power inherently requires more transmission capacity per unit of delivered energy. In circumstances of limited transmission capacity, the wind power may be curtailed (or spilled), which depending on the contract arrangements may be a loss of revenue to the wind generator or an added cost to the grid operator, in the case of having a take or pay type contract with the wind generator. In either case, energy storage could be applied to mitigate the curtailment, i.e. store the otherwise wasted generation and dispatch it later when transmission capacity is available and market conditions warrant. This would also defer or avoid any transmission upgrade that would be required to affect the same savings. Whereas an integrated G&T utility with the ability to accrue both benefits may find the economics of the energy storage system worthy, the single benefit to either G or T entity is not likely to do so. Should the G entity investing in energy storage receive a credit/payment for the value of the transmission deferral or avoidance, as approved by the regulator? Alternatively, should the regulated T entity investing in energy storage capture the value of the otherwise wasted energy and hence be motivated for the lowest total cost of service to the rate payers, not necessarily the lowest transmission cost? Such issues pervade the deployment of energy storage systems within the restructured utility industry.

In addition to the opportunities created by the constraints of and impact on the grid due to intermittent wind power resources, there are other energy storage based opportunities that result from the ability to firm and shape the wind generation to better respond to market economic conditions. In open markets for generation, regulation control and spinning reserve, the wind generator is able to apply energy storage to firm and shape a portion of the wind generation in order to optimize the overall economics, with higher firm energy prices and capacity credits. For example, in cases with a stronger wind resource at night and/or a higher price for energy during the day, energy storage can serve to shift a portion of the nightly low value, off-peak wind generation to the high value, peak period on a diurnal basis. Further, if the circumstances of the wind power at night also align with a minimum load such that the wind causes a grid stability problem (or is being curtailed to avoid such problems), then the energy storage also serves as a varying load at night to alleviate the stability problem (or curtailment) as well as a varying generator during the day to optimize the wind revenues.

Where wind generation is bid to the open market based on forecast models, energy storage systems can serve as a hedge to the forecasting uncertainty and hence further optimize the wind revenues, by shifting non-firm generation from higher than forecast deliveries to avoid the penalties associated with lower than forecast deliveries. The advanced wind power markets, e.g. Denmark and Germany, apply an hourly imbalance period for settling the over-under forecast imbalance penalties which yield the highest values for such energy storage applications.

Altogether, energy storage systems offer a broad range of potential for optimizing grid connected wind power resources, along with challenges and issues associated with technology deployment plus institutional ownership arrangements and related sharing of benefits. Such is the content of this Supplement.

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3
WIND APPLICATIONS FOR BENEFIT – COST ASSESSMENTS

The Handbook addresses T&D system energy storage applications within four categories – Grid Stability, Grid Operational Support, Distribution Power Quality and Daily Load Shifting. The reader is referred to the Handbook for the details of those applications. This Supplement to the Handbook adds a fifth category – Wind Generation Support (WGS) – that addresses grid connected wind applications of energy storage that enhance the utilization of such wind resources.

Description of Single Function WGS Applications of Energy Storage

Transmission Curtailment (TC)

A study conducted for the Texas State Energy Conservation Office [1] describes circumstances in which wind developers installed more wind generation in a region than the transmission infrastructure can transfer from that region. Such conditions may occur at wind farm sites remote from population centers for which extension of transmission capacity to service generation and loads in the area has not yet been justified. Figure 3-1 illustrates the relationship between wind farm output and available transmission capacity adapted from Reference 1 for use in the assessment of Transmission Curtailment (TC) applications in this Supplement. Note that the staircase profile is the result of how the wind profile was incrementally converted in Reference 1 to a power profile. For these conditions and except for underground CAES, delivery of output from a 60 MW wind farm is constrained to 50 MW by available transmission about 2200 hours per year.

The mitigation of constraints imposed by insufficient transmission capacity on the utilization of wind generation requires that energy be stored during periods of insufficient transmission capacity and discharged when capacity becomes available. The duty cycle imposed by the Texas wind profile requires that the energy storage system be maintained at low state-of-charge for extended periods so that energy can be stored when transmission constraints occur, as well as accommodate an economic number of charge-discharge cycles. The energy storage duty cycle for first 1500 hours of a year for TC applications is illustrated in Figure 3-2.

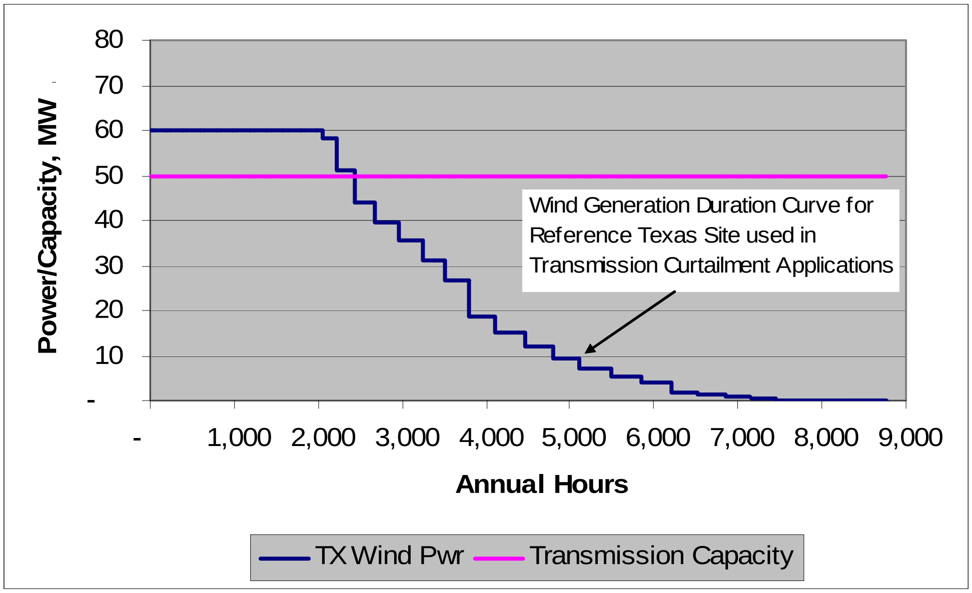

Figure 3-1
Wind Generation Curtailed by Available Transmission Capacity

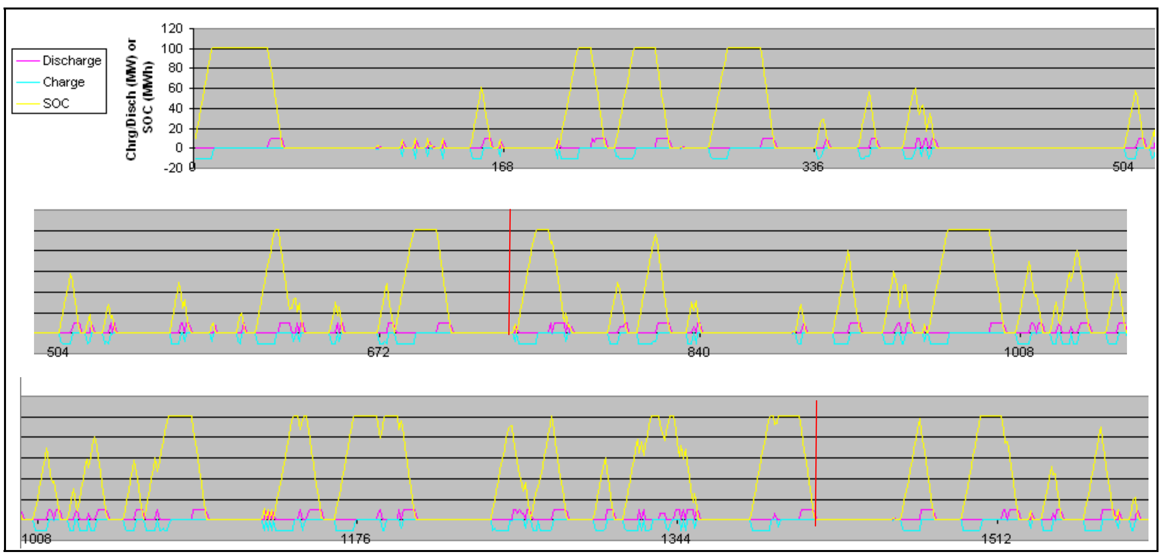

Figure 3-2
Example Energy Storage Duty Cycle for Transmission Curtailment Applications (units on abscissa are hours, red lines indicate end of January and February)

Time-Shifting (TS)

For the purposes of this Supplement, wind generation time-shifting pertains to storing energy generated during daily periods of low demand (off-peak, 6:00 pm to 6:00 am) for discharge during periods of high demand (on-peak, 6:00 am to 6:00 pm). It is also assumed that the energy storage system will be fully utilized, i.e., that power is purchased from the grid when off-peak wind generation is insufficient to completely charge the energy storage media. The wind generation duration curve used in the assessment of TS applications is shown in Figure 3-3. This hourly average profile data was provided by NREL as representative of wind farms in the upper Midwest. Figure 3-4 illustrates the energy storage system duty cycle for TS applications.

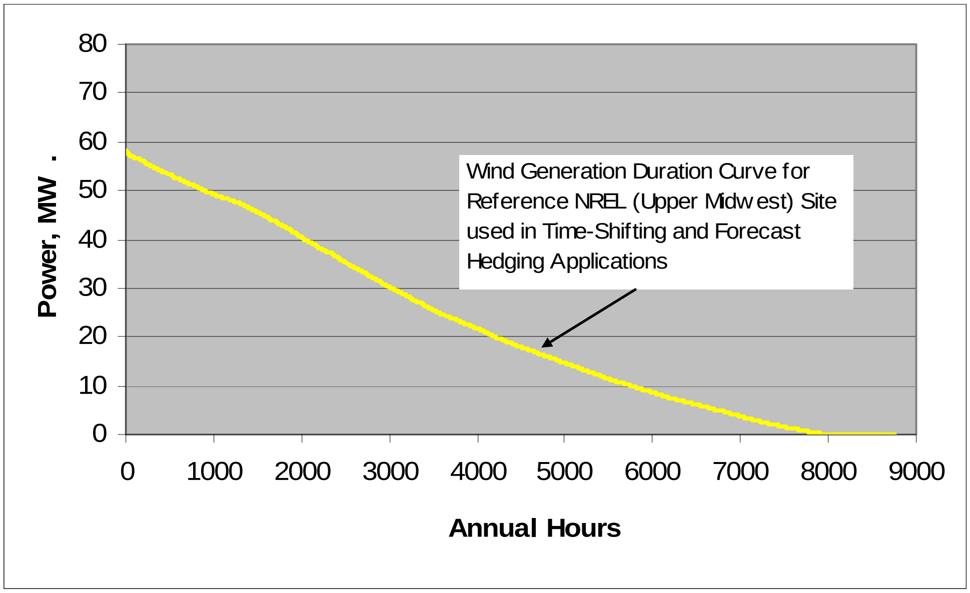

Figure 3-3
Wind Generation Duration Profile for Time-Shifting and Forecast Hedging Applications

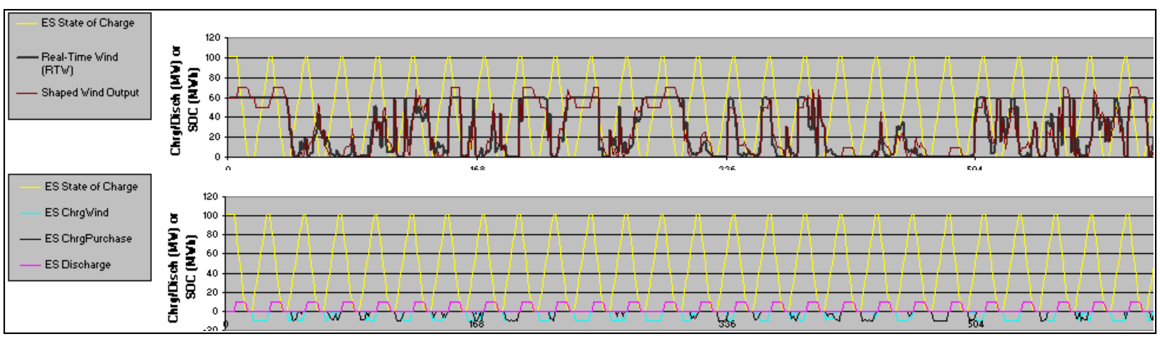

Figure 3-4
Example Energy Storage Duty Cycle for Time Shifting Applications (units on abscissa are hours)

Forecast Hedging (FH)

Wind generation forecast hedging applications would use stored energy to mitigate penalties incurred when real-time generation falls short of the amount of generation bid for delivery. The scheduling scheme used by the California Independent System Operation (CAISO) requires that bids for the delivery of generation be placed 2.5 hours ahead of the hour for delivery [2]. Short term variability in wind farm output results in an economic risk that real-time generation will be more or less than the bid amount, and these risks are managed by using a combination of wind generation forecasting techniques and bidding strategies to minimize penalties due to shortfalls (i.e., the amount supplied less than amount bid). Experience in Denmark [3] indicates that average deviation between forecast and real-time wind generation averages about 6%.

The value of energy storage to mitigate shortfalls in forecasts of the NREL wind profile (Figure 3-3) is assessed by using a simple persistence forecast model for a 3-hour ahead bidding market and adjusting the average deviation to 6%. Figure 3-5 shows a representative duty cycle for the FH application.

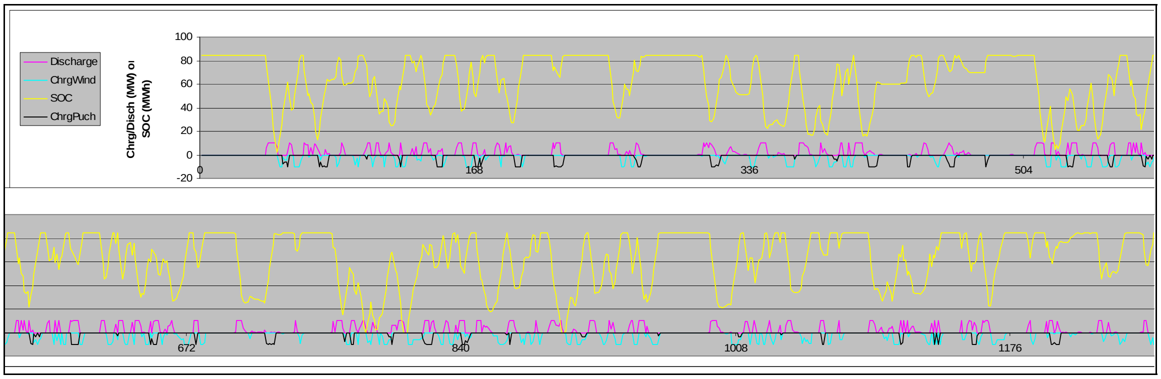

Figure 3-5
Example Energy Storage Duty Cycle for Forecast Hedging Applications (units on abscissa are hours)

Grid Frequency Support (GFX)

Functionally, grid frequency support for wind generation is very similar to Application C, Frequency Excursion Suppression (GFS), described in the Handbook. Both applications provide short duration power necessary to maintain grid frequency steady within a nominal range following a severe system disturbance caused by, or resulting in, a significant imbalance between generation and load. In systems with a high fraction of generation provided by wind generation, a sudden reduction in wind can cause such a disturbance. (As noted in the references, a 50% step reduction of rated capacity in wind generation over a one-hour period has been observed in a large U.S. wind farm [4], and German operators have observed up to a 90% drop, or 3640 MW_{ac} within 6 hours, with an average of 10 MW_{ac} per minute [5].

While such disturbances are usually addressed by conventional spinning reserve assets, those markets are predisposed to minimize the use of conventional generation. Such premium “green markets” can utilize the “prompt” response offered by some energy storage systems to support the grid until alternative strategies can be implemented (e.g., dispatchable loads). Further, such storage systems may be charged with excess wind energy.

Fluctuation Suppression (FS)

Wind fluctuation suppression applications would use stored energy to stabilize wind farm generation frequency by absorbing and discharging energy counter to high cycle variations in output. Dynamic simulations indicate that the energy storage duty cycle shown in Figure 3-6 would stabilize a wind farm with an average output of 12 MW_{ac} [6]. For the purposes of assessments herein, the profile shown in Figure 3-6 is assumed to be continuous.

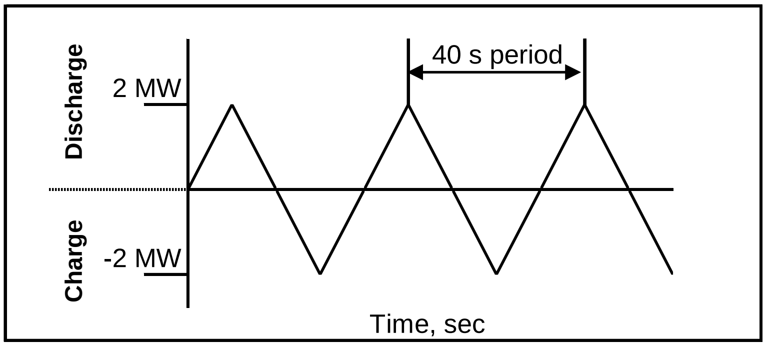

Figure 3-6
Example: Energy Storage Duty Cycle to Suppress Fluctuations in Wind Generation

The duty cycle in Figure 3-6 can be accommodated with energy storage media with very high cycle life, i.e., over 15 million cycles are required over the 20 year project life. Flywheel and ultracapacitor energy storage are the leading candidates for this single function application and are assessed as a rated power level of 2 MW_{ac}[1]. Note, this application is typically at the wind farm in order to make the wind power compliant with stability criteria imposed by the transmission operator. Hence, this is a special case within the otherwise grid based applications of energy storage.

For grid based applications, the benefits from bulk energy storage technologies for combined fluctuation suppression and time-shifting may be considered. Figure 3-7 illustrates the duty cycle used herein for NAS, VRB and CAES systems which are assessed at a rated power level of 10 MW_{ac}. For these applications, the energy storage media experiences the fluctuation suppression profile as continuously varying discharge and charge conditions adapted for a 24-hour period, while the grid is exposed to dispatchable generation and loads over those intervals. Cycle life limited energy storage media such as NAS and VRB are thus exposed to one cycle per day.

[1] In conducting assessments of energy storage options for this application, this duty cycle was been found to be onerous for short duration energy storage media such as ultracapacitors and flywheels. This suggests that the requirement to continuously mitigate fluctuations may be overly severe and should be reconsidered in light of actual wind data in future evaluations. The results of this study should not preclude the consideration of such technologies in similar applications with less rigorous requirements.

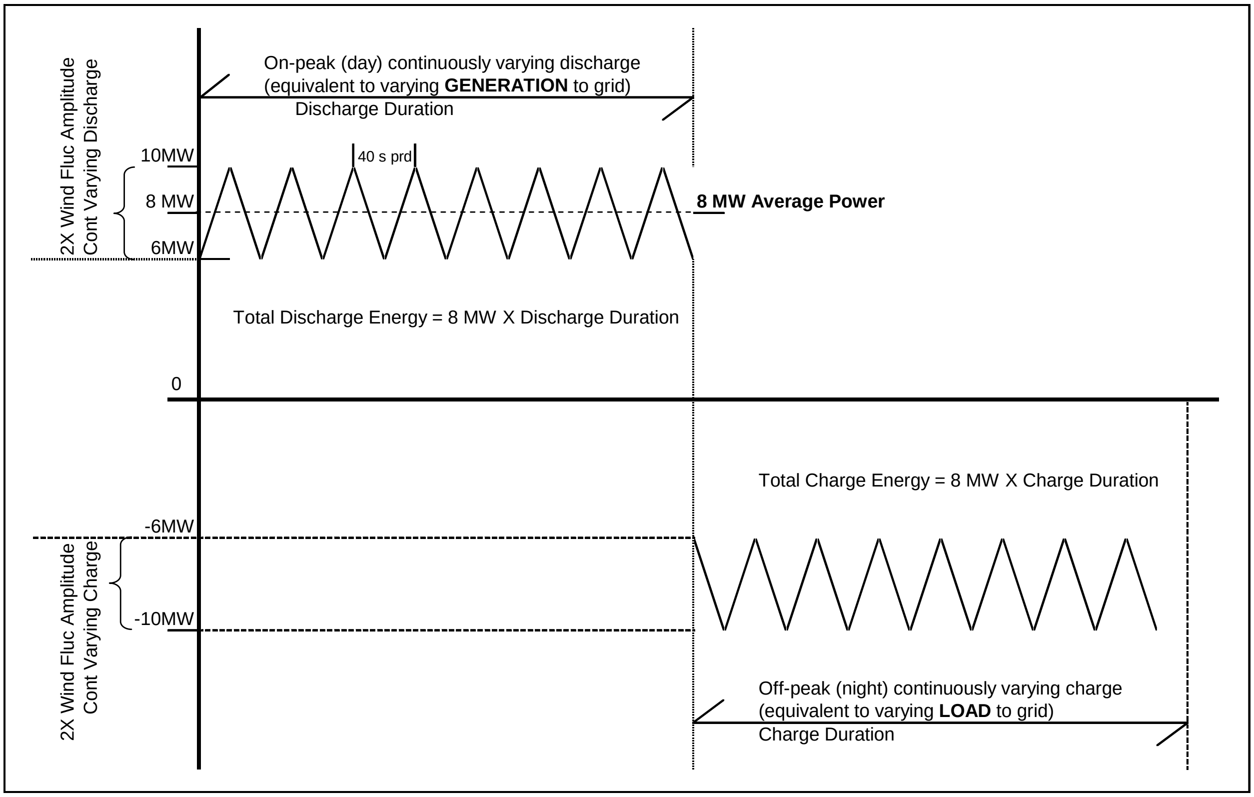

Figure 3-7
Example: Duty Cycle for Bulk Energy Storage in Combined Fluctuation Suppression and Time-Shifting Applications

Summary of Single Function Applications and Top-Level Energy Storage System Requirements

The single function wind generation applications described in terms of the grid phenomena to be mitigated and/or the power market opportunity to be exploited in the preceding section have been selected for inclusion in this Supplement to the Handbook. These five single function applications complement the nine applications (Applications A through I) currently in the Handbook. For the convenience of the reader, Table 3-1 from the Handbook lists the key requirements for Applications A through I. Table 3-2 lists corresponding key requirements for the five applications addressed in this Supplement (Applications J through L). These requirements also provide the bases for combined function applications described in the section titled, Energy Storage Technology Suitability for T&D Applications.

As indicated in Tables 3-2, the reference power and voltage selected for TC, TS, FH and GFX Wind Generation Support applications (with the exception of large Compressed Air Energy Storage (CAES)) are 10 MW_{ac} and 13.8 kV, respectively. Because wind fluctuations are typically an issue for small wind farms that are a significant fraction of the transmission load, the reference power for Application N has been chosen to be 2 MW_{ac}. These values are used in selecting unit configurations and determining the costs of the electronic power conversion and energy storage systems addressed herein. The choice of unit size was made in light of the primary objective of the Handbook to improve insight to emerging energy storage technologies in T&D applications, as well as in recognition of the stage of development of those technologies and the likely size range of utility projects within the next few years. With regard to CAES, unit sizes of both 10 and 300 MW_{ac} are assessed, where the former is oriented to above grade installations employing fabricated pressure retention devices (pipes, pressure vessels, etc.) and the latter to subterranean geologic features. CAES power conversion is accomplished by mechanical rather than electronic means; hence, the normalization of PCS is not addressed for CAES.

Table 3-1
Top-Level Energy Storage System Requirements for T&D Applications A – I (Addressed in the Handbook)

Applications / Parameters	Grid Stabilization (GS)			Grid Operational Support (GOS)		Distribution Power Quality (PQ)		Load-Shifting (LS)	
	Angular Stability (GAS) A	Voltage Stability (GVS) B	Frequency Excursion Suppression (GFS) C	Regulation Control (RC) D	Conventional Spinning Reserve (SR) E	Short Duration PQ (SPQ) F	Long Duration PQ (LPQ) G	Short Duration LS (LS3) H	Long Duration LS (LS10) I
ES System Unit Power, MW	10 to 500 (10)	10 to 500 (10)	10 to 500 (10)	2 to 200 (10)	2 to 200 (10)	1 to 50 (10)	1 to 50 (10)	1 to 200 (10)	1 to 200 (10)
ES System AC Voltage, kV	4.2 to 750 (13.8)	4.2 to 750 (13.8)	4.2 to 750 (13.8)	4.2 to 115 (13.8)	4.2 to 115 (13.8)	4.2 to 34.5 (13.8)	4.2 to 34.5 (13.8)	4.2 to 115 (13.8)	4.2 to 115 (13.8)
Equivalent Full Power Discharge Duration	few seconds (1 sec)	few seconds (1 sec)	10 to 30 min (15 min)	3 to 30 min (7.5 min)	2 hr max (2 hr)	seconds (2 sec)	hours (4 hrs)	1 to 4 hrs (3)	5 to 12 hrs (10)
Energy Discharged Per Event	10 MJ to 1 GJ (10 MJ)	5 MJ to 30 GJ (10 MJ)	0.2 to 25 MWh (2.5 MWh)	0.1 to 25 MWh (2.5 MWh)	2 to 100 MWh (20 MWh)	2 MJ to 3 GJ (50 MJ)	1 to 400 MWh (40 MWh)	1 to 200 MWh (30 MWh)	5 to 600 MWh (100 MWh)
Energy Discharge Duty Cycle	10 events/yr 1 event/d 20 cyc/event	10 events/yr 1 event/d	10 events/yr 1 event/d	Continuous Market (Ref 2 cycles/hr)	10 events/yr 1 event/d	100 events/yr 5 events/d 1 event/hr	1 event/yr	60 events/yr 1 event/d	250 events/yr 1 event/d
System Response Time	< 20 msec	< 20 msec	< 20 msec	<10 min	<10 min	< 20 msec	< 20 msec	<10 min	<10 min
Basis for Economic Benefits	Capitalized Costs and Benefits of Alternative System			Market Rates		Capitalized Costs and Benefits of Alternative System		Reduced T Demand Charge, plus Δ Energy Savings plus Capitalized Costs and Benefits of Alternative System	

Table 3-2
Top-Level Energy Storage System Requirements for Wind Applications J – N (Addressed in this Supplement)

Applications / Parameters	Wind Generation Support (WGS)				
	Trans-mission Curtail-ment (TC)	**Time-Shifting (TS)**	**Forecast Hedge (FH)**	**Grid Frequency Support (GFX)**	**Fluctuation Suppression (FS)**
	J	**K**	**L**	**M**	**N**
ES System Unit Power, MW	2 to 200 (10)	2 to 200 (10)	2 to 200 (10)	2 to 200 (10)	2 to 50 (2)
ES System AC Voltage, kV	4.2 to 34.5 (13.8)	4.2 to 34.5 (13.8)	4.2 to 34.5 (13.8)	4.2 to 34.5 (13.8)	4.2 to 34.5 (13.8)
Equivalent Full Power Discharge Duration	5 to 12 hrs (except large CAES) (varies by ES Technology)			10 to 30 min (15 min)	few seconds (10 sec)
Energy Discharged Per Event	50 to 120 MWh (except large CAES) (varies)			0.2 to 25 MWh (2.5 MWh)	10 to 200 MJ (20 MJ)
Energy Discharge Duty Cycle	Per reference wind profile, optimized for each technology			24 events/yr 1 event/d	Continuous triangular wave, Chrg & Disch, 90cy/hr
System Response Time	< 1 min	< 1 min	< 20 msec	< 20 msec	< 20 msec
Basis for Economic Benefits	Capitalized Costs and Benefits of Alternative System, Market Rates, Tax Credits, and Green Price Premiums				

Bases for economic evaluation are identified in this section, and the methodology for deriving benefits and costs is presented in Chapter 4. Key duty cycle requirements for each application listed in Table 3-2 are discussed in the following paragraphs:

Application J: Transmission Curtailment (TC) – These applications require that wind generated energy be stored during periods of constrained transmission and discharged when access to transmission becomes available. These conditions may occur at proximate to remote wind farms with marginal local transmission capacity. The energy storage system should respond within minutes and is available for other functions during periods of unconstrained transmission. The energy storage system duty cycle is dictated by the Texas wind profile as described above. This application is valued at market electricity rates for the incremental wind generation and capacity delivered, plus the value of avoided T&D upgrade

Application K: Time-Shifting (TS) – These applications require that wind generated energy be stored during daily periods of low demand (off-peak, 6:00 pm to 6:00 am) for discharge during periods of high demand (on-peak, 6:00 am to 6:00 pm). They also require that the energy storage system be fully utilized, i.e., that power be purchased from the grid when off-peak wind generation is insufficient to completely charge the energy storage media. The energy storage system should respond within minutes and is available for compatible concurrent functions, e.g., regulation control. The energy storage system duty cycle is dictated by the NREL wind profile as described above. This application is valued at time of use markets and, on a case basis, the costs and benefits of avoided peaking generation.

Application L: Forecast Hedge (FH) – These applications require that wind generated energy in excess of bid amounts be stored, and wind generation less than bid amounts be supplemented with stored energy on a real-time basis. They also require that the energy storage system be fully utilized, i.e., that power be purchased from the grid during periods of excess energy (i.e. more than forecast) and, as needed, during off-peak periods. The energy storage system should respond within a 20 milliseconds and is available for compatible concurrent functions, e.g., regulation control. The energy storage system duty cycle is dictated by the NREL wind profile as described above. This application is valued at time of use market rates.

Application M: Grid Frequency Support (GFX) – These applications require "prompt" spinning reserve to mitigate imbalances between wind generation and load and may arise with sudden loss of wind generation (e. g, 50% of rated power over an hour) in systems with a high degree of wind penetration (e.g., greater than about 20%). The energy storage system must detect the disturbance and respond within 20 milliseconds by injecting real power for up to 30 minutes. The reference duty cycle for analysis is hot standby for infrequent events characterized by 15-minute full power discharge (FPD), 1 event per day, 10 events per year. This application is valued at the cost of alternative solutions.

Application N: Fluctuation Suppression (FS) – These applications require continuous response to wind output fluctuations at the rate of 90 cycles per hour over the life of the system. The reference duty cycle for FS alone and FS plus TS applications are illustrated in Figures 3-6 and 3-7. This application is valued at the cost of alternative solutions.

Energy Storage Technology Suitability for T&D Applications

For the convenience of the reader, the suitability of the energy storage technologies addressed in the Handbook for T&D Applications A through I is summarized in Table 3-3. The suitability of the energy storage technologies addressed in this Supplement for Wind Generation Support (Applications J through N) is summarized in Table 3-4. These characterizations are based on the performance and cost parameters contributed from the vendor contributors and the screening economic analyses conducted for the Handbook and this Supplement. The reader will find a detailed economic assessment in the respective technology chapters for each technology/application combination indicated by a checkmark "✓" (for benefit to cost ratios greater than 1.0) or an "M" (marginal, for ratios less than 1.0, but greater than .8 and deemed to have economic potential for reasons described within the respective technology chapter). This framework is intended as a guide for use in the initial consideration of energy storage systems within T&D applications and should not be viewed as a constraint on the applicability of a technology. As with the Handbook, the purpose is to screen leading energy storage systems against leading candidate wind related applications. For site-specific project deployment considerations, the utility/user should work with the selected vendors in order to fully optimize the energy storage system to the application.

Table 3-3
T&D Applications A through I – Energy Storage Technology Suitability Matrix (Addressed in the Handbook)

Category			Application	Energy Storage Technology: PbA	NiCad	NAS	ZnBr	VRB	Regenesys	SMES	Flywheels	Ultracaps	CAES (10 MW above grade)	CAES (135 MW below grade)
Grid Stabilization (GS)			A: Angular Stability (GAS)	✓	M		M			✓	✓	✓		
			B: Voltage Stability (GVS)	✓						M		M		
			C::Frequency Excursion Suppression (GFS)	M	M									
Grid Operational Support (GOS)			D: Regulation Control (RC)											✓
			E: Cnvntnl Spinning Reserve (SR)											
Distribution Power Quality (PQ)			F: Short Duration PQ (SPQ)	✓	✓	✓	✓			✓	✓	✓		
			G: Long Duration PQ (LPQ)	M										
Load-Shifting (LS)			H: 3 hr (LS3)										✓	
			I: 10h (LS10)			✓		✓	✓				✓	✓
Combined Applications	"T" Utility	C1: GFS +	GAS+ GVS+ RC	M	M	M								
	"D" Utility	C2: SPQ +	LS10 + RC + SR			✓		✓	✓					
		C3: SPQ +	LS3 + RC + SR	✓	✓	✓	✓	✓	✓					
		C4: LPQ +	LS3 + RC + SR	✓		✓		M	✓					
	"T" or "D"	C5: LS10 +	RC + SR			✓	M	✓	✓				✓	✓

Table 3-4
T&D Applications J through N – Energy Storage Technology Suitability Matrix (Addressed in this Supplement)

Category		Application	Energy Storage Technology							
			PbA	NiCad	NAS	VRB	Flywheels	Ultracaps	CAES (10 MW above grade)	CAES (300 MW below grade)
Wind Generation Support (WGS)		J. Transmission Curtailment (TC)							M	✓
		K. Time-Shifting (TS)							✓	✓
		L. Forecast Hedge (FH)			M				✓	✓
		M. Grid Frequency Support (GFX)	M	M						
		N. Fluctuation Suppression (FS)					M*	M*		
Combined Applications	C6: TC +	GFX, RC			M	✓			✓**	✓**
	C7: TS +	GFX, RC			✓	M			✓**	✓**
	C8: FH +	GFX, RC			✓	✓			✓**	✓**
	C9: FS+	GFX, TS			✓	M			✓**	

* M* denotes potential for less demanding duty cycle see footnote, p. 3-5.
** ✓** denotes that the GFX application is excluded

Table 3-4 also introduces "combined function applications" which address energy storage systems adapted to serve multiple functions (e.g., C6 represents combined transmission curtailment, grid frequency support and regulation control applications). In the analysis of combined function applications, it is necessary to define functional priorities. The priority applications for applications C6 through C9 are; respectively, TC, TS, FH and FS. The approach used herein is to first size the reference energy storage system to meet the requirements of the priority application and then add functions incrementally (in the order listed), to identify an economic optimal configuration that utilizes system attributes (e.g., cycle life) to the fullest extent practical. In doing so, care is taken to realistically estimate the implications of the combined duty cycles in terms of managing the state-of-charge, thermal or flow management and cycle life.

Note that combined applications for CAES systems shown in Table 3-4 exclude the GFX function, which is defined herein as requiring a "prompt" spinning reserve response. Hence, the GFX value is not included in the CAES benefit assessment for the applications so indicated. Note also that the large CAES is not applicable for the FS application, which is associated with small scale wind farms that represent a significant fraction of the transmission load.

Application Summary Descriptions

For consistency, the following summaries of the foregoing applications appear in the applications assessment sections for each energy storage technology in their respective chapters. The applications addressed for that technology are indicated by a border enclosing the summary. Applications J through N are addressed in this Supplement. Summaries for Applications A through I addressed in the Handbook are included for the convenience of the reader.

Single Function Applications

Application A: Grid Angular Stability (GAS) – mitigation of power oscillations by injection and absorption of real power at periods of 1 to 2 seconds. The reference duty cycle for analysis is standby for infrequent events characterized by 20 oscillatory cycles, cumulatively equivalent to a full power discharge (FPD) of 1 second duration and subsequent charge cycle; 1 event per day; 10 events per year. Valued at the cost of alternative solutions.

Application B: Grid Voltage Stability (GVS) – mitigation of degraded voltage by additional reactive power plus injection of real power for durations up to 2 seconds. The reference duty cycle for analysis is standby for infrequent events characterized by 1 second FPD, 1 event per day, 10 events per year. Valued at the cost of alternative solutions.

Application C: Grid Frequency Excursion Suppression (GFS) – "prompt" spinning reserve (or load) for mitigating load-generation imbalance. Requires energy storage to discharge real power for durations up to 30 minutes. The reference duty cycle for analysis is standby for infrequent events characterized by 15 minute FPD, 1 event per day, 10 events per year. Valued at the cost of alternative solutions.

Application D: Regulation Control (RC) – system frequency regulation in concert with load following. The reference duty cycle for analysis is characterized by continuous cycles equivalent to 7.5-minute FPD and charge cycle (triangular waveform), 2 cycles per hour deployed with 10 minutes advance notice. Valued at market rates.

Application E: Spinning Reserve (SR) – reserve power for at least 2 hours with 10 minute notice. The reference duty cycle for analysis is standby for infrequent events characterized by 2 hour FPD, 1 event per day, 10 events per year. Valued at market rates.

Application F: Short Duration Power Quality (SPQ) – capability to mitigate voltage sags (e.g. recloser events). The reference duty cycle for analysis is standby for infrequent events characterized by 2 seconds FPD, 1 event per hour, 5 events per day, 100 events per year. Valued at the cost of alternative solutions.

Application G: Long Duration Power Quality (LPQ) – SPQ, plus capability to provide several hours reserve power. The reference duty cycle for analysis is standby for infrequent events characterized by SPQ plus standby for 4 hours FPD, 1 event per year. Valued at the cost of alternative solutions.

Application H: 3-hr Load Shifting (LS3) – shifting 3 hours of stored energy from periods of low value to periods of high value. The reference duty cycle for analysis is scheduled 3-hour FPD, 1 event per day, 60 events per year. Valued at market rates.

Application I: 10-hr Load Shifting (LS10) – shifting 10 hours of stored energy from periods of low value to periods of high value. The reference duty cycle for analysis is scheduled 10-hour FPD, 1 event per day, 250 events per year. Valued at market rates.

Application J: Transmission Curtailment (TC) – mitigation of power delivery constraint imposed by insufficient transmission capacity. Except for large CAES, reference duty cycle for analysis is derived from the reference 60 MW Texas wind farm profile constrained to 50 MW by available transmission capacity, valued at market electricity rates for the incremental wind generation and capacity delivered, plus the value of avoided T&D upgrade.

Application K: Time-Shifting (TS) – firms and shapes wind generation via the reference NREL wind profile by storing wind generation during the off-peak interval (6:00 pm to 6:00 am), supplemented by power purchased from the grid when wind generation is inadequate, and discharged during the on-peak interval (6:00 am to 6:00 pm). Valued at the market rates for the time-shifted, shaped energy and capacity; plus the value of avoided peaking generation upgrade.

Application L: Forecast Hedge (FH) – mitigates errors (shortfalls) in wind energy bid three hours prior to a one-hour delivery interval via the reference NREL wind profile. Valued at the incremental value of wind energy and capacity delivered at market rates and avoided penalties.

Application M: Grid Frequency Support (GFX) – supports grid frequency during sudden large decreases in wind generation and similar to GFS above, i.e., "prompt" spinning reserve (or load) for mitigating load-generation imbalance. Requires energy storage to discharge real power for durations up to 30 minutes. The reference duty cycle for analysis is standby for infrequent events characterized by 15 minute FPD, 1 event per day, 24 events per year. Valued at the cost of alternative solutions..

Application N: Fluctuation Suppression (FS) – stabilizes wind farm generation frequency by suppressing fluctuations (continuously absorbing and discharging energy during short duration variations in output) at a rate of 90 cycles per hour over the life of the project. Valued at the cost of alternative solutions.

<u>Combined Function Applications (In the Order Noted)</u>

Application C1: Combined Applications C, A, B, D (GFS +GAS + GVS + RC)

Application C2: Combined Applications F, I, D, E (SPQ + LS10 + RC + SR)

Application C3: Combined Applications F, H, D, E (SPQ + LS3 + RC + SR)

Application C4: Combined Applications G, H, D, E (LPQ + LS3 + RC + SR)

Application C5: Combined Applications I, D, E (LS10 + RC + SR)

Application C6: Combined Applications J, M, D (TC + GFX + RC)

Application C7: Combined Applications K, M, D (TS + GFX + RC)

Application C8: Combined Applications L, M, D (FH + GFX + RC)

Application C9: Combined Applications N, M, K (FS + GFX + TS)

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6. Communications with Ken Mattern, S&C Electric, August 2004.

4 ENERGY STORAGE BENEFITS AND BENEFIT QUANTIFICATION

Introduction

Consistent with the Handbook, this chapter addresses the benefits associated with the specific grid connected wind power applications identified in Chapter 3 and serves as the bases for quantifying such benefits for the energy storage technologies in their respective chapters. As before, the benefits are addressed from the perspective of an integrated utility, which may not be fully accrued by a separate T utility or wind generator. As in the preceding Chapter 4, only the incremental content needed for the wind applications is included. For background and detail on the approach for quantifying the benefits of energy storage, see Chapter 4 of the Handbook.

Benefits from Deferral or Avoidance of Alternative Costs

The net present value (NPV) of the alternative solutions for the applicable wind applications is summarized in Table 4-1, including the nominal value and a range of reasonable high and low values for the extrapolative application of the results. Consistent with the Handbook, single point analyses are based on the nominal NPV of the alternative solution and results are shown graphically for the range. Note that the combined applications may apply two deferral benefits (e.g., combined TC, GFX and RC), where both TC and GFX warrant two alternative solution benefits. These values are consistent with the Handbook; however, TC applications are treated slightly different.

Table 4-1
Valuation of Alternative Solutions

	Application	Reference Alternative System & Nominal NPV	Value Range Used in Economic Assessments, $/kW		
			PbA, NiCad NAS, VRB, FES, UC	**CAES 10 MW_{ac}**	**CAES 300 MW_{ac}**
Single Functions	J: Transmission Curtailment (TC)	Transmission expansion ~$750/kW	500 to 1000		
	K: Time Shift (TS)	NA Apply market rates			
	L: Forecast Hedge (FH)	NA Apply market rates			
	M: Grid Frequency Support (GFX)	Additional spinning reserves ~$750/kW	500 to 1000	NA	
	N: Fluctuation Suppression (FS))	Additional regulation control assets ~$750/kW	500 to 1000		NA
Combined Functions	C6: TC +GFX +RC	Transmission expansion and added spinning reserves ~$1500/kW	1000 to 2000	500 to 1000	
	C7: TS + GFX + RC	Additional spinning reserves ~$750/kW	500 to 1000	NA	
	C8: FH + GFX + RC	Additional spinning reserves ~$750/kW	500 to 1000	NA	
	C9: FS + GFX + TS	Additional spinning reserves and regulation control assets ~$1500/kW	1000 to 2000	500 to 1000	NA

The alternative solution for the TC application is a transmission upgrade (TU) that avoids curtailment. However, this alternative solution is unlike others in the Handbook in that its value includes value components that are quantitatively different from those of the energy storage (ES) solution. Specifically, value components for the TU solution include the capitalized value of all wind generation at non-firm energy rates that would have been curtailed. These TU values are quantitatively different from the capitalized value of revenue from the ES solution, which include revenue from the sale of energy at firm rates and capacity credits, offset by the storage efficiency and any unutilized curtailed wind. Treating this difference in value components in the same manner as other solutions in the Handbook causes cumbersome graphical presentation of results. To remedy this problem for transmission curtailment applications while retaining the same results charting format used elsewhere in the Handbook, values on the abscissa represent the range of NPV <u>costs of TU</u>, while energy storage value shown on the ordinate are derived from <u>ES costs plus the difference in benefit values</u>. The mathematical relationships are as follow:

Net NPV = NPV (Benefits) – NPV (Costs)

B_{TU} = NPV Benefits of Transmission Upgrade
C_{TU} = NPV Costs of Transmission Upgrade

B_{ES} = NPV Benefits of Energy Storage
C_{ES} = NPV Cost of Energy Storage

Therefore, value parity between the transmission upgrade (TU) and energy storage (ES) solutions may be expressed as $B_{TU} – C_{TU} = B_{ES} – C_{ES.}$ Solving for energy storage cost, C_{ES}, yields $C_{ES} = C_{TU +} B_{ES} - B_{TU}$, or $C_{ES} = C_{TU} + (B_{ES} - B_{TU})$, in which the term $(B_{ES} - B_{TU})$ is the differential benefits (e.g., difference in revenue from sale of power) between the ES and TU solutions. As a general statement, ES solutions are cost effective when TU costs exceed ES costs plus the difference in ES and TU benefits.

For example, assume the NPV of the benefits for the transmission upgrade from non-firm energy revenue is $1000/kW and the NPV of the benefits for the energy storage solution is $1350/kW. The latter derives from the added value for firm rates and the capacity credit, offset by the inefficiency of the storage system plus any limitations for capturing all of the curtailed wind. The difference is $350/kW which, when added to the NPV of the deferred or avoided NPV of the cost of transmission expansion, results in the breakeven NPV of the costs for the energy storage solution. The breakeven capital cost of the energy storage subsystem of the ES solution is obtained by subtracting the cost contributions for the PCS, BOP, O&M and disposal.

Benefits from Firm Energy and Capacity Credits

An intrinsic value of energy storage applied to wind power resources, is the ability to firm and shape that portion delivered through the energy storage system and hence gain the dispatchable benefits associated with firm energy prices, plus a capacity credit, versus the otherwise non-firm energy prices. Table 4-2 provides such reference firm and non firm values for an assumed peak and off-peak time-of day rate structure. Also included are the penalty prices for imbalance payments that result from shortfalls in energy deliveries relative to the bid quantities based on wind forecast models. (Penalties are only introduced in Forecast Hedging applications.)

Table 4-2
Valuation Parameters for Wind Energy and Capacity Credit

Electricity Market Rates	Firm Energy $/MWh	Non-Firm Energy $/MWh	Capacity Credit $/kW-mo
Wind Generation Market for On-Peak (6:00 am to 6:00 pm)			
Market Rates	120	60	6
Bid Shortfall Penalties	130		

Table 4-2 (continued)
Valuation Parameters for Wind Energy and Capacity Credit

Electricity Market Rates	Firm Energy $/MWh	Non-Firm Energy $/MWh	Capacity Credit $/kW-mo
Wind Generation Market for Off-Peak (6:00 pm to 6:00 am)			
Market Rates	60	30	6
Bid Shortfall Penalties	70		

The values in Table 4-2 were selected as representative of target opportunities for the TS application, i.e. shifting non-firm wind generation from the off-peak night to firm priced energy with a capacity credit to the on-peak day, plus the FH application that shifts greater than forecast energy throughout the day and night to avoid the imbalance payment penalties associated with delivering less than forecast energy. It is noted that the firm energy prices are higher than the corresponding peak and off-peak rates applied for load shifting valuations in the Handbook. The increased values are attributed to the "green power" premiums that accrue to wind power resources. It is also noted that the capacity credit is unique to wind applications within the Handbook effort. The value is based on ISO New England experience for firm generation [1], however, capacity credits are not provided in all open markets.

Valuation of Energy Storage Based on Hourly Wind Data

As described in Chapter 3, the energy storage duty cycles for TC, TS and FH applications are based on wind profiles representative of a Texas (TC) and an upper Midwest (TS and FH) wind farm sites. These wind profiles consist of average hourly data for a recent year. The methodology used to analyze the applications was adapted from recent methodology developed by Ridge Energy Storage and Grid Services as part of a study on the use of energy storage conducted for the Texas State Energy Conservation Office [2]. Examples of the approach to deriving the value of energy storage for TC, TS and FH applications are provided in the following paragraphs.

Valuation of Energy Storage for Transmission Curtailment Applications

Transmission curtailment occurs when transmission capacity is less than wind generation capacity. Table 4-3 summarizes the economic characterization of an 1800 MW_{ac} wind farm for which transmission is constrained to 1500 MW_{ac}. Within the time-of-day rate structure described above, the value of the full potential generation of the site is shown in the row labeled "Direct Wind", and value of curtailed wind generation is shown in the row labeled "Curtailed Wind". Thus, the annual revenue for the constrained wind farm is shown as about $261 million per year. For this example, a 300 MW CAES installation with 12,000 MWh_{ac} (40 hours) storage capacity is used to mitigate this constraint. As shown in the lower portion of Table 4-3, both the "Direct Wind" and "Curtailed Wind" contributions are significantly reduced relative to the constrained case since energy is stored during periods of transmission constraint and discharged when transmission capacity is available. Since stored energy can be reliably dispatched, the other value components associated with energy storage are firm energy and capacity credits. Thus, the annual revenue for the wind farm with energy storage is about $322.3 million per year.

The resultant value of energy storage with respect to a system with constrained transmission is about $2,100/kW. Note, this is the value from the perspective of the wind generator or CAES system owner, without consideration of a transmission upgrade alternative.

Table 4-3
300 MW CAES Valuation for Transmission Curtailment from: 1800 MW Generation Curtailed to 1500 MW

	On-Peak 6:00 am to 6:00 pm			Off-Peak 6:00 pm to 6:00 am		
Electric Rates	Firm $/MWh	Non-Firm $/MWh	Capacity $/kW-mo	Firm $/MWh	Non-Firm $/MWh	Capacity $/kW-mo
Rates	120	60	6	60	30	6
Penalties	(130)			(70)		
Curtailed 1800 MW Wind Farm - 1500 MW Transmission Capacity - NO Energy Storage, K$/yr						
Direct Wind		189,339			101,016	
Curtailed Wind		(18,664)			(10,656)	
Net Annual Revenue, K$/yr	**261,035**					
1800 MW Wind Farm - WITH Energy Storage						
Direct Wind		171,573			91,080	
Curtailed Wind		(1,111)			(828)	
Stored Energy to Market	51,575		3,533	21,196		2,904
(Fuel Use at 5$/mmBtu)	(17,619)					
Net Annual Revenue, K$/yr	**322,302**					
Net Value of Energy Storage, $/kW	**2,082**					

However, as described earlier in this chapter, the alternative to energy storage from an integrated G and T utility for TC applications is a transmission upgrade to eliminate curtailment. Table 4-4 summarizes the related energy value analyses.

Table 4-4
300 MW CAES Valuation for Transmission Curtailment: 1800 MW Generation with NO Curtailment

	On-Peak 6:00 am to 6:00 pm			Off-Peak 6:00 pm to 6:00 am		
Electric Rates	Firm $/MWh	Non-Firm $/MWh	Capacity $/kW-mo	Firm $/MWh	Non-Firm $/MWh	Capacity $/kW-mo
Rates	120	60	6	60	30	6
Penalties	(130)			(70)		
1800 MW Wind Farm - 1800 MW Transmission Capacity - NO Energy Storage, K$/yr						
Direct Wind		189,339			101,016	
Curtailed Wind						
Net Annual Revenue, K$/yr	**290,355**					
1800 MW Wind Farm - WITH Energy Storage						
Direct Wind		171,573			91,080	
Curtailed Wind		(1,111)			(828)	
Stored Energy to Market	51,575		3,533	21,196		2,904
(Fuel Use at 5$/mmBtu)	(17,619)					
Net Annual Revenue, K$/yr	**322,302**					
Net Value of Energy Storage, $/kW	**1,086**					

In this case, there is no curtailment, and the value of full potential generation of the site shown in the row labeled “Direct Wind” is about $290.3 million. Value components for the wind farm equipped with energy storage are the same as described before, and the value of energy storage with respect to a system with unconstrained transmission is about $1,100/kW. Combining this value with the avoided cost of a transmission upgrade valued at $750/kW results in a net NPV of $1,850/kW. This value is the breakeven NPV for the CAES system cost. Hence, from the perspective of the integrated G and T utility, the most appropriate alternative solution (therefore, the target breakeven NPV for the CAES system cost) is a transmission upgrade. Note that the Handbook and this Supplement are oriented to the perspective of the G and T utility, but both perspectives on valuation are valid.

Valuation of Energy Storage for Time-Shifting Applications

Time-shifting energy storage applications take advantages of the on-/off-peak rate differential, as well as the recognition that stored energy warrants firm energy rates and capacity credits. Table 4-5 summarizes the economic characterization of a 60 MW_{ac} wind farm within the time-of-day rate structure described above. The value of the full potential generation of the site is shown in the row labeled “Potential Wind Generation”, for which the annual value is about $8.8 million. For this example, a 10 MW_{ac} CAES installation with 100 MWh_{ac} (10 hours) storage capacity is used.

As shown in the lower portion of Table 4-5, the value of the off-peak portion of “Direct Wind” is significantly reduced relative to the “Potential Wind Generation” above, since energy is stored during off-peak periods and discharge during the on-peak period. In this application, off-peak wind generation is supplemented with purchased power from the grid so that the capacity of the energy storage media is fully utilized. Since stored energy can be reliably dispatched, the other value components associated with energy storage are firm energy and capacity credits. Thus, the annual revenue for the wind farm with energy storage is about $11.6 million.

The capitalized value (based on Handbook reference fixed charge rate of 9.8 %/yr) of energy storage configured for time-shifting with respect to the potential wind generation sold at non-firm rates farm is about $2800/kW

Table 4-5
10 MW CAES Valuation for Time-Shifting Applications

	On-Peak 6:00 am to 6:00 pm			Off-Peak 6:00 pm to 6:00 am		
Electric Rates	Firm $/MWh	Non-Firm $/MWh	Capacity $/kW-mo	Firm $/MWh	Non-Firm $/MWh	Capacity $/kW-mo
Rates	120	60	6	60	30	6
Penalties	(130)			(70)		
60 MW Wind Farm - NO Energy Storage, K$/yr						
Potential Wind Generation		5,864			2,976	
Net Annual Revenue, K$/yr	**8,840**					
60 MW Wind Farm - WITH Energy Storage, K$/yr						
Direct Wind		5,864			2,141	
Stored Energy to Market	5,256		360			
(Value Wind to Storage)					(836)	
(Value Purch Enrg to Storage)					(215)	
(Fuel Use at 5$/mmBtu)	(986)					
Net Annual Revenue, K$/yr	**11,585**					
Net Value of Energy Storage, $/kW	**2,798**					

Valuation of Energy Storage for Forecast Hedging Applications

Forecast hedging energy storage applications combine wind forecasting techniques and prompt utilization of stored energy to reliably supply dispatchable power within the bid interval. Table 4-6 summarizes the economic characterization of a 60 MW_{ac} wind farm for which generation is bid into a 3-hour ahead market as described in Chapter 3. Within the time-of-use rate structure described above, bidders commit to deliver power at firm rates, subject to shortfall penalties and overages valued at non-firm rates. In the case without energy storage, a bidding strategy is adopted that results in an optimal combination of bidding at values below the forecast and penalties for shortfalls. Analytically, the bid amount, expressed as percent of forecast, is obtained by iterative calculation to identify the maximize revenue. As shown in the table, the bidding strategy for case without energy storage is based on 90% of the forecast value, resulting in a shortfall penalty of about $1.2 million per year.

For this example, the 10 MW_{ac} CAES installation is optimally sized with about 6 hours of storage or 60 MWh_{ac}. As shown in the lower portion of Table 4-6, the value of the on-/off-peak non-firm portion of “Direct Wind” is significantly reduced relative to the “Potential Wind Generation”, since wind energy greater than the bid amount is stored for discharge at firm rates during a subsequent bid interval. In this application, excess generation (greater than bid) is supplemented with off-peak purchased power from the grid so that the capacity of the energy storage media is fully utilized. In the case with energy storage, the optimal bidding strategy is 100% of the forecast amount and penalties are reduced to about $0.5 million per year.

The capitalized value of energy storage configured for forecast hedging with respect to the potential wind generation sold only on the basis of forecasts is about $1600/kW

Table 4-6
10 MW CAES Valuation for Forecast Hedging Applications

	On-Peak 6:00 am to 6:00 pm			Off-Peak 6:00 pm to 6:00 am		
Electric Rates	Firm $/MWh	Non-Firm $/MWh	Capacity $/kW-mo	Firm $/MWh	Non-Firm $/MWh	Capacity $/kW-mo
Rates	120	60	6	60	30	6
Penalties	(130)			(70)		
Wind Farm - NO Energy Storage - Bid @ 90% Forecast, K$/yr						
Potential Wind Generation	9,950	888	524	4,955	499	540
(Shortfall Penalty)	(822)			(379)		
Net Annual Revenue, K$/yr	**16,157**					
Wind Farm - WITH Energy Storage - Bid @ 100% Forecast, K$/yr						
Direct Wind	10,635	373	543	5,319	204	544
Stored Energy to Market	972			413		
(Shortfall Penalty)	(316)			(157)		
(Value Wind to Storage)		(173)			(113)	
(Value Purch Enrg to Storage)					(160)	
(Fuel Use at 5$/mmBtu)	(337)					
Net Annual Revenue, K$/yr	**17,747**					
Net Value of Energy Storage, $/kW	**1,621**					

Ancillary Services Benefits

In the combined applications, Regulation Control (RC) is included in all but one as a result of insights from the Handbook of the complementary duty cycles and relatively high incremental values for many of the energy storage systems of interests. Accordingly, the same RC value of 16$/MW-hr, developed in the Handbook, is applied in the Supplement.

References

1. Summary of the Calculation of the Levelized Annual Cost of Constructing a New Peaking Resource in New England, e-Acumen Advisory Services report to ISO New England, December 10, 2001

2. Study Of Electric Transmission in Conjunction With Energy Storage Technology, by the Lower Colorado River Authority, for the Texas State Energy Conservation Office, August 21, 2003

5
COMMON FINANCIAL PARAMETERS AND COST ELEMENTS

As would be expected, the Handbook content for this chapter applies directly to this wind Supplement to the Handbook, including the financial groundrules, parameters and methodology; the approach for sizing and costing the Power Conversion System (PCS); and the approach for costing the Balance of Plant (BOP). No additional common parameters or cost elements are required for the wind related applications herein.

Hence, this chapter is brief and is limited to Table 5-1, identifying PCS cost and voltage window data for Applications A through I addressed in the Handbook, and Table 5-2 listing those PCS properties for Applications J through N addressed in this Supplement. These tables provide the resultant summary of the bases for PCS selection and costs used for the wind application assessments presented within the respective energy storage technology chapters. For more detailed information on financial parameters and common cost elements used in this Supplement, see Chapter 5 of the Handbook.

Table 5-1
Summary of PCS Cost and Voltage Windows by Technology and Application (Applications A through I, Addressed in the Handbook)

Category	No	Application	PCS Selection Bases Events					PCS Cost Bases		
			Priority Application	Response Time	Frequency	Event Duration	VAR Support	PCS Type	Capital, $/kW	Operating
Grid Stabilization (GS)	A	Angular Instability (GAS)	GAS	<20msec	20 cycles/event, 10 events/yr, 1 event/d	1 sec	Secondary	I or III	$13,500*V_{min}^{-0.59}$, or $365*P_f^{-0.54}$	Include standby losses
	B	Voltage Instability (GVS)	GVS		10 events/yr, 1 event/d	1 sec	Priority	I	$13,500*V_{min}^{-0.59}$	
	C	Frequency Support (GFS)	GFS		10 events/yr, 1 event/d	15 min	Secondary	I	$13,500*V_{min}^{-0.59}$	
Grid Operational Support (GOS)	D	Regulation Control (RC)	RC	≤10min	1 to 20 cycles/hr (2 cycles/hr)	7.5 min		II	$11,500*V_{min}^{-0.59}$	No standby
	E	Cnvntnl Spinning Reserve (SR)	SR		10 events/yr, (10 events/yr, 1 event/d)	2 hr		II	$11,500*V_{min}^{-0.59}$	
Distribution Power Quality (PQ)	F	Short Duration PQ (SPQ)	SPQ	<20msec	100 events/yr, 5 events/d, 1 event/hr	5 sec		I or III	$13,500*V_{min}^{-0.59}$, or $365*P_f^{-0.54}$	Include standby losses
	G	Long Duration PQ (LPQ)	LPQ		1 event/yr	4 hr		I	$13,500*V_{min}^{-0.59}$ + $50/kW for static switch	
Load-Shifting (LS)	H	3 hr (LS3)	LS3	≤10min	60d/yr	3 hr		II	$11,500*V_{min}^{-0.59}$	No standby
	I	10 hr (LS10)	LS10		250d/yr	10 hr		II	$11,500*V_{min}^{-0.59}$	
Combined Applications: "T" Utility, GFS+	C1	GAS+ GVS+ RC	GFS	<20msec	Combined per above		Priority (GVS)	I	$13,500*V_{min}^{-0.59}$	Include standby losses
Combined Applications: "D" Utility, SPQ +	C2	LS10 + RC + SR	SPQ				Secondary	I or III	$13,500*V_{min}^{-0.59}$, or $365*P_f^{-0.54}$	
Combined Applications: "D" Utility, SPQ +	C3	LS3 + RC + SR	SPQ					I or III	$13,500*V_{min}^{-0.59}$, or $365*P_f^{-0.54}$	
Combined Applications: "D" Utility, LPQ +	C4	LS3 + RC + SR	LPQ					I	$13,500*V_{min}^{-0.59}$ + $50/kW for static switch	
Combined Applications: "T" or "D", LS10 +	C5	RC + SR	LS10	≤10min				II	$11,500*V_{min}^{-0.59}$	No standby

Table 5-2
Summary of PCS Cost and Voltage Windows by Technology and Application
(Applications J through N, Addressed in this Supplement)

Category			No	Application	PCS Selection Basis Event					PCS Cost Bases		
					Priority Application	Response Time	Frequency	Event Duration	VAR Support	PCS Type	Capital, $/kW	Operating
Wind Generation Support (WGS)			J	Transmission Curtailment (TC)	TC	<1 min	Texas Wind Profile		Secondary	II	11,500*Vmin$^{-0.}$[illegible]	Include standby losses
			K	Time Shifting (TS)	TS		NREL Wind Profile					
			L	Forecast Hedging (FH)	FH	<20msec				I	13,500*Vmin$^{-0.}$[illegible]	
			M	Grid Frequency Support (GFX)	GFX		24 events/yr 1 event/day	15 min				
			N	Fluctuation Suppression (FS)	FS		Continuous triangular wave, 90cy/hr	10 sec				No standby
Combined Applications	"G" & "T" Utility	TC +	C6	GFX + RC	GFS		Combined per above					Include standby losses
		GAS +		GVI + LS3 + RC +								
		TS +	C7	GFX + RC	SPQ							
		FH +	C8	GFX + RC	SPQ							
		FS+	C9	GFX + TS	LPQ							No standby

6
LEAD-ACID BATTERIES

Update Overview

As might be expected for a mature technology, few significant developments in lead-acid battery technology have occurred over the last year. While incremental improvements in technology have been made, none are of a magnitude to warrant updating the technical or economic parameters described in the original Handbook.

Perhaps the most substantial development has been a technology put forward by a company called Firefly Energy. Firefly, a spin-off from industrial equipment manufacturer Caterpillar, Inc. (which still owns a stake in the company), has developed a new lead-acid technology based on a composite grid material impregnated with lead material. The composite grid has higher conductivity, lighter weight, and longer life than a traditional lead-allow grid, without diverging significantly from the manufacturing processes for a traditional lead-acid battery. While the company has not yet introduced a product, future development will be worth watching [1, 2].

Wind Power Generation Experience

Lead-acid batteries are very commonly used for small wind power applications, especially for standalone remote power installations smaller than 100 kW_{ac}. Small wind power generators require some energy storage, as they seldom have other prime movers to compensate for the variability of the wind. Most batteries used in these applications are VRLA batteries specially designed for renewable applications such as wind and solar.

For larger standalone wind power installations, diesel generators become more cost-effective than batteries, and are more commonly used. Lead-acid batteries are generally not used for larger grid-connected wind farms: the size of the batteries required, as well as the replacement occasioned by their relatively short cycle life, makes their use uneconomic to compensate for short-duration or long-duration variability at that scale.

Lead-acid batteries have been investigated for stabilization of grid-connected wind turbines. In the U.S. during 1992 and 1993, a 2.88 MW_{ac} and 17.28 MWh_{ac} lead-acid battery facility was operated integral with wind generation in the San Gorgonio area of California by a private wind developer. The project was the second or third largest battery storage project ever built at that time. It operated successfully for two annual peak seasons for the purpose of meeting firm capacity contract obligations prior to the repowering of an early wind farm. The batteries were surplus submarine batteries that were packaged in 360 kW modules with six hours storage [3].

The most well-known field demonstration was conducted by the Institute of Applied Energy (IAE), a Japanese research foundation based in Tokyo and dedicated to finding system solutions to energy and environmental issues. In 2000, IAE was commissioned by the New Energy and Industrial Technology Development Organization (NEDO), a Japanese government agency, to conduct a field study for the stabilization of output of wind turbines with storage batteries [4]. The resulting project proposed to investigate the use of energy storage to mitigate power fluctuations as a result of wind gusts.

Three projects were funded by NEDO through IAE, one of which was the installation of a VRLA battery at the Tohoku EPC Cape Tappi Number 7 wind turbine. The VRLA battery was sized to provide 200 kW_{ac} for four hours, and was paired with a single 300 kW_{ac} wind turbine to provide stabilization for fluctuations in wind power output and energy shifting to deliver power at times of high demand rather than low demand. The test of the VRLA system began in April 2001 and ran for eight months. Despite being considered a success overall, the VRLA system was not followed with future development [5].

Lead-acid technology, because of its relatively short cycle life, is poorly suited for applications that require energy storage of significant duration, particularly if charge and discharge is required a large part of the year. For this reason lead-acid batteries are not considered a viable alternative for the long-duration applications described in this Supplement. However, they are a viable candidate for the grid frequency support (GFX), consistent with the earlier Handbook results.

Select Wind Applications for Lead-Acid Battery Systems

This section presents the select applications for which the lead-acid battery system is suited and describes the key features of such when configured to meet the requirements of those applications. Screening economic analyses have shown that lead-acid battery systems are potentially competitive for one of the single function applications and all of the combined function applications described in detail in Chapter 3. The following list briefly summarizes and reiterates key requirements for all applications. Those for which lead-acid system is best suited are enclosed by borders.

Single Function Applications

Application J: Transmission Curtailment (TC) – mitigation of power delivery constraint imposed by insufficient transmission capacity. Except for large CAES, reference duty cycle for analysis is derived from the reference 60 MW Texas wind farm profile constrained to 50 MW by available transmission capacity, valued at market electricity rates for the incremental wind generation and capacity delivered, plus the value of avoided T&D upgrade.

Application K: Time-Shifting (TS) – firms and shapes wind generation via the reference NREL wind profile by storing wind generation during the off-peak interval (6:00 pm to 6:00 am), supplemented by power purchased from the grid when wind generation is inadequate, and discharged during the on-peak interval (6:00 am to 6:00 pm). Valued at the market rates for the time-shifted, shaped energy and capacity; plus the value of avoided peaking generation upgrade.

Application L: Forecast Hedge (FH) – mitigates errors (shortfalls) in wind energy bid three hours prior to a one-hour delivery interval via the reference NREL wind profile. Valued at the incremental value of wind energy and capacity delivered at market rates and avoided penalties.

Application M: Grid Frequency Support (GFX) – supports grid frequency during sudden large decreases in wind generation and similar to GFS above, i.e., "prompt" spinning reserve (or load) for mitigating load-generation imbalance. Requires energy storage to discharge real power for durations up to 30 minutes. The reference duty cycle for analysis is standby for infrequent events characterized by 15 minute FPD, 1 event per day, 10 events per year. Valued at the cost of alternative solutions..

Application N: Fluctuation Suppression (FS) – stabilizes wind farm generation frequency by suppressing fluctuations (absorbing and discharging energy during short duration variations in output). Valued at the cost of alternative solutions.

Combined Function Applications (In the Order Noted)

Application C6: Combined Applications J, M, D (TC + GFX + RC)

Application C7: Combined Applications K, M, D (TS + GFX + RC)

Application C8: Combined Applications L, M, D (FH + GFX + RC)

Application C9: Combined Applications N, M, K (FS + GFX + TS)

Lead-Acid Battery System Compliance with Application Requirements

Lead-acid performance parameters discussed in the Handbook were used to develop approximate sizes and operational parameters for systems meeting the application requirements for the selected GFX application described in the previous section. Key factors in sizing lead-acid systems include:

- Duration of the discharge. For applications requiring very short discharge, a SLI battery may be sufficient. For longer discharges, a stationary cell would be more appropriate.
- Depth of discharge. Lead-antimony cells are more appropriate for deep-discharge systems, while lead-calcium cells can be used to minimize standby losses if deep discharge is not required.
- Selection of the type of PCS and pulse factor (which determines the minimum discharge voltage and therefore the PCS cost as described in Section 5 of the Handbook).
- State-of-charge management to ensure that the required power and energy are accessible and that the battery is appropriately recharged.
- Thermal management to ensure that cell temperatures are maintained within the acceptable range and that the rate of heat loss is appropriate to the application.
- Cycle life management to ensure that the system is operated within the service life of equipment, which is especially important for combined function, high cycle applications such as load shifting with regulation control.

Performance aspects of lead-acid battery systems for the selected application are described below and summarized in Table 6-1. The reference power for all applications is 10 MW_{ac}. In each of these applications, several possible products can be used to build the system. In the examples below, the systems are designed with a specific product by way of example, and should not be understood to advocate a particular product for this application.

- **Application M:** Grid Frequency Support (GFX) – This application requires that the system continuously detect and mitigate infrequent frequency excursions, up to 24 events per year. Stationary cells must be used in this application, and the relatively frequent duty cycle requires us to employ lead-antimony cells rather than lead-calcium. For this example, we connect GNB NAX-33 multipurpose stationary cells to produce series strings, each 1000 cells long. Three such strings are connected in parallel, and connected to a Type I PCS sized for a minimum discharge voltage of 1750 V_{dc}. The net efficiency of the battery is 97.9%. The battery can be expected to last 15 years.

Table 6-1
Lead Acid Battery System Compliance with Application Requirements

Applications	Single Function **App M: GFX - Grid Frequency Support**
Energy Storage Selection	
Type of Product	GNB NAX-33
Number of Strings	3
Pulse Factor	1.0
Max Charge Voltage	0
Min Discharge Voltage	1,750
Maximum DOD, %	100%
Cumulative Cycle Fraction	5%
Replacement Interval, yr	15
PCS Selection	
PCS Type (Chapter 5)	I
Duty Cycles **Grid Support or Power Quality (GS or PQ)**	
Power, MW	10
Event Duration, Hr	0.25
Summary System Data	
Standby Hours per Year	8,739
System Net Efficiency, %	97.9%
Energy Storage Standby Efficiency, %	99.9%
PCS Standby Efficiency, %	98.0%
System Footprint, MW/sqft (MW/m^2)	0.0012 (0.013)
Energy Storage Footprint, MW/sqft (MW/m^2)	0.0014 (0.0153)
Note: System net efficiency includes losses for energy conversion and system standby expressed on an annual basis, i.e., one minus inefficiency, where inefficiency equals the ratio of annual energy losses to the product of system rated power times 8760 hours, expressed in percent.	

Benefit and Cost Analyses

Lead-Acid Battery Pricing and Integrated System Costs

Lead-acid batteries are mature, well-established products with commodity pricing. Changes over time will be dependent largely on fluctuations in the commodity price of lead. The pricing of batteries is often dependent on the number of products bought at once. Large orders can often bring significant discounts on the price of batteries.

For the Handbook's specified deployment date of 2006 and rating of 10 MW_{ac}, the prices are based on manufacturers' quotes from 2003 for bulk quantities of batteries, including interconnection hardware and racks. Replacement modules over the assumed 20-year project life are assumed to follow the same cost structure.

Lead-Acid Product	2003 Bulk Prices, $
GNB NAX-33 Stationary Single Cell (Lead-Antimony)	$700
GNB NAX-33 1000-Cell String	$802,000

For the stationary cell systems, the related scope of supply includes the cells themselves, the cell interconnection hardware, mounting racks, automated watering systems, and compressed air electrolyte agitation. The racks are assumed to be 2-tier back-to-back racks designed for seismic zone 1.

The cost of integrated lead-acid systems is obtained by combining the cost of the lead-acid battery scope of supply with the appropriate PCS and BOP costs. The PCS includes the power converter plus the grid disconnect and breaker protection, transformers, controller(s) to synchronize one or more lead-acid strings with the grid, and all equipment necessary for serving the load and isolating the lead-acid battery system. The BOP scope of supply consists of grid connection at the point of common coupling, land and improvements (e.g., access, services, etc.). The BOP cost is set at a nominal cost of $100/kW for the stationary cell systems. The PCS and BOP costs shown in Table 6-2 are based on the methodology described in Chapter 5 of the Handbook. The cost of enclosure is not included in the scope of supply for stationary batteries, so that the cost of interior space, foundations for the batteries, and HVAC installation is included at $100/sqft in accordance with general past experience.

Table 6-2
Capital and Operating Costs for Lead Acid Battery Systems

Applications	Single Function
	App M: GFX - Grid Frequency Support
Battery Capacity, MWh_{ac}	3
PCS Initial Cost, $/kW	165
BOP Initial Cost, $/kW	100
Battery Initial Cost $/kW	315
Battery Initial Cost $/kWh	1,258
Total Capital Cost, M$	5.8
O&M Cost – Fixed, $/kW-year	16.5
O&M Cost– Variable, $/kW-year	7.0
NPV Disposal Cost, $/kW	0.8

Note: The total initial cost may be calculated in two ways:
1. By mutiplying the sum of PCS, BOP and Battery initial costs expressed in $/kW by the reference power,
2. OR by mutiplying the sum of PCS and BOP expressed in $/kW by the reference power and then adding the product of Battery Initial cost expressed in $/kWh and the Battery Capacity

Fixed O&M costs are based on $2/kW for the PCS as required by provisions in Chapter 5 of the Handbook, plus battery maintenance in accordance with the vendor. This maintenance varies depending on the type of battery and the application. Fixed O&M costs are based on labor costs of $50 per hour.

The recommended maintenance program for stationary batteries consists of continuous remote monitoring and detailed inspections conducted four times a year, which include:

- Visual inspection for damage, leakage, or other physical problems with cells, interconnections, and connecting cables

- Cleaning the tops and sides of cells to remove dirt and deposited electrolyte salts
- Measurement of voltage, resistance, and specific gravity of electrolyte for each cell
- Measurement of resistance between terminals of adjacent cells
- Retorquing terminal connections as necessary
- Confirming the accuracy of DC voltage, DC current, and temperature sensors as necessary

In addition, stationary cells require the addition of water to replace water lost during charging and standby periods. Lead-antimony batteries require more frequent watering than lead-calcium batteries. Batteries undergoing frequent cycling require more frequent watering than batteries that spend most of their time on standby. In these assessments, the frequency of water addition varies between once a year for a lead-calcium battery on standby, to once a month for a lead-antimony battery undergoing regular cycling.

In addition, an allowance for annual property taxes and insurance, based on 2% of the initial total capital costs, is included in the fixed O&M costs.

Variable O&M costs for the system include the cost of electrical losses to maintain the PCS and the battery during hot standby intervals.

An allowance for lead-acid battery disposal costs is also included at the end of battery life, covering the cost of removing the battery from the plant. Although old batteries can be sold for scrap, the prices are quite low and are not included in this analysis.

Lifecycle Benefit and Cost Analysis for Lead-Acid Battery Systems

Further insight to the value of energy storage can be gained through lifecycle cost analyses using a net present value (NPV) methodology and comparison with alternatives. The financial parameters in Table 6-3 are used to assess the applications described in the preceding section.

Table 6-3
Financial Parameters

Dollar Value	2003
System Startup	June 2006
Project Life, years	20
Discount Rate (before tax), %	7.5
Property Taxes & Insurance, %/year	2
Fixed Charge Rate, %/year	9.81

The results of lifecycle cost benefit analyses of select lead-acid battery applications are summarized in Table 6-4 and discussed below. The bases and methodology used in valuing energy storage applications is described in detail in Chapter 4. The details of the cost benefit analysis for each application are discussed below.

Table 6-4
Summary of Benefit and Cost Analyses of Lead-Acid Battery Systems

Applications	Single Function App M: GFX - Grid Frequency Support
Alt Solution Value, $/kW	750
Initial Installed Cost, M$	5.79
Total Costs, M$	(8.6)
Total Benefits, M$	7.5
Benefit to Cost Ratio	0.87
NPV, M$	(1.1)
Battery Type	GNB NAX-33 1000-cell string
Number of Modules	3
Battery 2006 Price, K$/module	802
Battery Price for NPV=0, K$/module	539

- Application M: Grid Frequency Support (GFX) – This application was evaluated on the assumption that an alternative system capable of mitigating GFX events can be obtained for capitalized acquisition and operating costs of $750/kW, including acquisition, fixed and variable O&M, and property taxes and insurance costs. As shown in Table 6-4, this application yields a negative NPV of $(1.1) million on an initial investment of $5.8 million. As a measure of sensitivity of NPV with respect to alternative system costs, Figure 6-1 illustrates the change in NPV over a range of $500 to $1000/kW and shows that lead-acid systems compete favorably against alternative solutions with net capitalized costs in excess of about $860/kW. As an additional indicator of NPV sensitivity with respect to the cost of energy storage, if the price of the lead-acid string were decreased from $802 to $539 thousand per string, the NPV would equal zero, i.e., costs and benefits would be equal with those for alternative solutions valued at $750/kW.

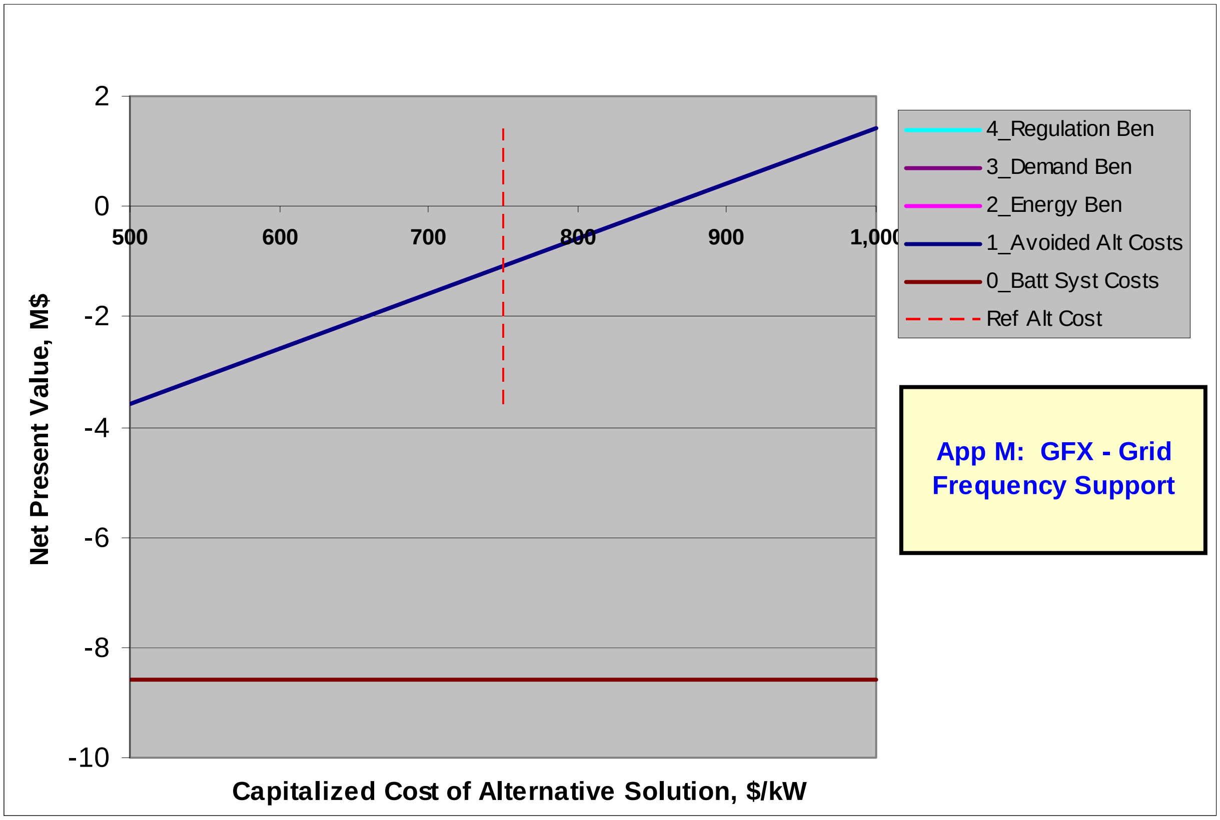

Figure 6-1
Application M: Lead-Acid System NPV vs Cost of Alternative System

Interpreting Results From Benefit-Cost Analyses

In general, lead-acid battery systems are expected to be marginally competitive for GFX applications where the NPV of the alternative solution is in the range of about $850/kW.

The reader is reminded that the foregoing analyses are intended as a guide to the initial consideration of energy storage options, and that these analyses are based on representative electric rates and costs for alternative systems as described in Chapter 4. The assumptions used herein should be reviewed in light of project specific applications, alternative solutions, electric rates and financial parameters.

References

1. Firefly Energy Website, www.fireflyenergy.com

2. G. Woolf. “Glimmer of Hope in New Lead Design,” Batteries and Energy Storage Technology, Summer 2004, p. 61-64.

3. Communications with Hal Romanowitz with Oak Creek Energy Systems, December 2004, plus see Chapter 12 of Wind Power in Power Systems, Edited by T. Ackerman, John Wiley & Sons, Publication expected in January 2005.

4. NEDO Press Release, September 7, 2000.

5. NEDO, "Investigation into the Possible Use of Storage Batteries for Stabilization of Wind Power Generation," February 2002.

7
NICKEL-CADMIUM AND OTHER NICKEL ELECTRODE BATTERIES

Update Overview

Little has changed on the technology side of nickel-cadmium (NiCad) and other nickel electrode batteries in the year since the publication of the Handbook. Most development work in large batteries has focused on nickel-metal hydride batteries and their application in transportation applications such as hybrid automobiles. Some investigators have begun looking into the use of large nickel-metal hydride in other applications, such as substation batteries, although no significant field trials have taken place.

The most significant occurrence over the past year for utility-scale NiCad development has been the final testing and commissioning of the Golden Valley Electric Association (GVEA) facility at Fairbanks, Alaska. The GVEA project became fully operational in November 2003, and underwent acceptance testing in December 2004. The GVEA facility was discharged at its rated capacity of 27 MW_{ac} for 24 minutes, exceeding the specified requirement of 27 MW_{ac} for 15 minutes. It was also discharged at its peak capability of 46 MW_{ac} for 5 minutes, setting a new record for the most powerful battery in the world. The facility proved its worth over the succeeding months by protecting against a total of 46 outages, lasting a total of 435 minutes, in the eleven months from November 2003 through September 2004, preventing more than 225,000 customer disconnections [1].

Wind Power Generation Experience

Nickel-cadmium batteries, like lead-acid batteries, are sometimes used with small wind turbines (smaller than 100 kW_{ac}) in standalone remote power applications, where energy storage is required for compensation of the variability of the wind. For larger standalone systems, however, they are generally not as cost-effective as diesel generators. For grid-connected wind farms, nickel-cadmium batteries (and other nickel electrode batteries) will generally not be good economic solutions.

In a bulk storage application, nickel-cadmium batteries will be about three times as expensive as equivalent lead-acid batteries, while providing only about twice the cycle life. As with lead-acid batteries, it is not expected that nickel-cadmium batteries would be viable in this application. For this reason, nickel-cadmium batteries are not considered a viable alternative for the long-duration applications described in this Supplement. However, they are a viable candidate for the grid frequency support (GFX), consistent with the earlier Handbook results

Select Wind Applications for Nickel-Cadmium Energy Storage Systems

This section presents the select applications for which nickel-cadmium batteries are suited and describes the key features of nickel-cadmium systems when configured to meet the select application requirements. This application analysis has been restricted to nickel-cadmium because these are the only nickel electrode systems widely available for utility applications today. While large nickel-metal hydride products are available, these products are generally at a relatively early stage of development and have not shown clear advantages over flooded nickel-cadmium products.

Screening economic analyses have shown that nickel-cadmium systems are potentially competitive for the GFX (single function) application described in detail in Chapter 3. The following list briefly summarizes all of the Chapter 3 applications, with a reiteration of the key application requirements. Those for which nickel-cadmium systems are best suited are enclosed by borders.

Single Function Applications

Application J: Transmission Curtailment (TC) – mitigation of power delivery constraint imposed by insufficient transmission capacity. Except for large CAES, reference duty cycle for analysis is derived from the reference 60 MW Texas wind farm profile constrained to 50 MW by available transmission capacity, valued at market electricity rates for the incremental wind generation and capacity delivered, plus the value of avoided T&D upgrade.

Application K: Time-Shifting (TS) – firms and shapes wind generation via the reference NREL wind profile by storing wind generation during the off-peak interval (6:00 pm to 6:00 am), supplemented by power purchased from the grid when wind generation is inadequate, and discharged during the on-peak interval (6:00 am to 6:00 pm). Valued at the market rates for the time-shifted, shaped energy and capacity; plus the value of avoided peaking generation upgrade.

Application L: Forecast Hedge (FH) – mitigates errors (shortfalls) in wind energy bid three hours prior to a one-hour delivery interval via the reference NREL wind profile. Valued at the incremental value of wind energy and capacity delivered at market rates and avoided penalties.

Application M: Grid Frequency Support (GFX) – supports grid frequency during sudden large decreases in wind generation and similar to GFS above, i.e., “prompt” spinning reserve (or load) for mitigating load-generation imbalance. Requires energy storage to discharge real power for durations up to 30 minutes. The reference duty cycle for analysis is standby for infrequent events characterized by 15 minute FPD, 1 event per day, 10 events per year. Valued at the cost of alternative solutions..

Application N: Fluctuation Suppression (FS) – stabilizes wind farm generation frequency by suppressing fluctuations (absorbing and discharging energy during short duration variations in output). Valued at the cost of alternative solutions.

Combined Function Applications (In the Order Noted)

Application C6: Combined Applications J, M, D (TC + GFX + RC)

Application C7: Combined Applications K, M, D (TS + GFX + RC)

Application C8: Combined Applications L, M, D (FH + GFX + RC)

Application C9: Combined Applications N, M, K (FS + GFX + TS)

Nickel-Cadmium Energy Storage System Compliance with Application Requirements

The nickel-cadmium performance parameters discussed above were used to develop approximate sizes and operational parameters for systems meeting the application requirements for the selected applications described in the previous section. Key factors in sizing nickel-cadmium systems include:

- Duration of the discharge. For applications requiring very short discharge, a small high-rate sintered-plate battery would be appropriate. A cell with a higher ampere-hour rating would be better suited for longer discharges.
- Depth of discharge. Sintered-plate nickel-cadmium batteries are most appropriate when a large number of cycles are required. Pocket plate batteries may be used when fewer cycles are required.
- Selection of the type of PCS and pulse factor (which determines the minimum discharge voltage and therefore the PCS cost as described in Section 5).
- State-of-charge management to ensure that the required power and energy are accessible and that the battery is appropriately recharged.
- Thermal management to ensure that cell temperatures are maintained within the acceptable range and that the rate of heat loss is appropriate to the application.
- Cycle life management to ensure that the system is operated within the service life of equipment, which is especially important for combined function, high cycle applications such as load shifting with regulation control.

Performance aspects of nickel-cadmium energy storage systems for the GFX application are described below and summarized in Table 7-1. The reference power is 10 MW_{ac}. In this example, a representative nickel-cadmium product has been selected and sized for GFX applications. The selected product is appropriate for this application on the basis of technical and economic criteria. However, other products could also perform the same function.

- Application C: Grid Frequency Support (GFX) – This application requires that the system continuously detect and mitigate infrequent frequency excursions, for up to 24 events per year, requiring a discharge of about 15 minutes each. In this application energy, storage would be composed of large series strings of nickel-cadmium batteries. Two (2) strings, each composed of 2200 Saft Pocket Plate SBH 920 cells linked in series, would be connected to a Type I PCS. The system would be mounted on 5-tier racks. During most of the year, the system would be at standby, with an efficiency of 98%. The lifetime of this system would be dominated by calendar life rather than cycle life, so that the system is expected to last 15 years.

Table 7-1
Nickel-Cadmium System Compliance with Application Requirements

Applications	Single Function
	App M: GFX - Grid Frequency Support
Energy Storage Selection	
Type of Product	Saft Pocket Plate SBH 920, 220-Module String
Number of Strings	2
Pulse Factor	1.0
Max Charge Voltage	3,344
Min Discharge Voltage	2,200
Maximum DOD, %	80%
Cumulative Cycle Fraction	19%
Replacement Interval, yr	15
PCS Selection	
PCS Type (Chapter 5)	I
Duty Cycles	
Grid Support or Power Quality (GS or PQ)	
Power, MW	10
Event Duration, Hr	0.25
Summary System Data	
Standby Hours per Year	8,734
System Net Efficiency, %	98.0%
Energy Storage Standby Efficiency, %	100.0%
PCS Standby Efficiency, %	98.0%
System Footprint, MW/sqft (MW/m^2)	0.0045 (0.0483)
Energy Storage Footprint, MW/sqft (MW/m^2)	0.0106 (0.1137)

Note: System net efficiency includes losses for energy conversion and system standby expressed on an annual basis, i.e., one minus inefficiency, where inefficiency equals the ratio of annual energy losses to the product of system rated power times 8760 hours, expressed in percent.

Benefit and Cost Analyses

Nickel-Cadmium Energy Storage Pricing and Integrated System Costs

Nickel-cadmium batteries are mature, well-established products with commodity pricing. Changes over time will be dependent largely on fluctuations in the commodity prices of nickel and cadmium. The pricing of batteries is often dependent on the number of products bought at once. Large orders can often bring significant discounts on the price of batteries.

For the Handbook's specified deployment date of 2006 and rating of $10MW_{ac}$, the prices are based on manufacturers' quotes from 2003 for bulk quantities of batteries, including interconnection hardware and racks. Replacement modules over the assumed 20 year project life are assumed to follow the same cost structure.

Nickel-Cadmium Product	2003 Prices, $
Saft SBH 920 Battery 10-Cell Module	$7,780
Saft SBH 920 220-Module String	$1,712,000

The related scope of supply for these products includes the cells themselves, the cell interconnection hardware, and mounting racks

The cost of integrated nickel-cadmium systems is obtained by combining the cost of the nickel-cadmium product scope of supply with the appropriate PCS and BOP costs. The PCS and BOP costs shown in Table 7-2 are based on the methodology described in Chapter 5 of the Handbook. The BOP scope of supply consists of grid connection at the point of common coupling, land and improvements (e.g., access, services, etc.) and is based on a nominal cost of $100/kW. The nickel-cadmium systems described here would be located in interior space with environmental control. The cost for this space is included at $100/sqft. In addition, where 5-tier racks are used, space costs are increased by 20% to account for the requirement of a multi-story building.

Table 7-2
Capital and Operating Costs for Nickel-Cadmium Systems

Applications	Single Function: App M: GFX - Grid Frequency Support
Battery Capacity, MWh_{ac}	3
PCS Initial Cost, $/kW	144
BOP Initial Cost, $/kW	100
Battery Initial Cost $/kW	356
Battery Initial Cost $/kWh	1,424
Total Capital Cost, M$	6.0
O&M Cost – Fixed, $/kW-year	15.1
O&M Cost– Variable, $/kW-year	6.7
NPV Disposal Cost, $/kW	0.6

Note: The total initial cost may be calculated in two ways:
1. By mutiplying the sum of PCS, BOP and Battery initial costs expressed in $/kW by the reference power,
2. OR by mutiplying the sum of PCS and BOP expressed in $/kW by the reference power and then adding the product of Battery Initial cost expressed in $/kWh and the Battery Capacity

Fixed O&M costs are based on $2/kW for the PCS as prescribed in Chapter 5 of the Handbook, plus battery maintenance in accordance with the vendor. The recommended maintenance program for Saft batteries consists of continuous remote monitoring and detailed inspections conducted at regular intervals, which include:

- Visual inspection for damage, leakage, or other physical problems with cells, interconnections, and connecting cables
- Cleaning the tops and sides of cells to remove dirt and deposited electrolyte salts

- Measurement of voltage, resistance, and specific gravity of electrolyte for each cell
- Replacing water lost during charging
- Measurement of resistance between terminals of adjacent cells
- Retorquing terminal connections as necessary
- Confirming the accuracy of DC voltage, DC current, and temperature sensors as necessary

The duration between such inspections depends on the use of the system. Systems which are not cycled often may require maintenance once in two years. Commonly cycled systems may require maintenance twice a year or more.

The O&M figures provided here are estimates based on those made for the GVEA facility. Fixed O&M costs are based on labor costs of $50 per hour (or $900 per module per year). In addition, an allowance for annual property taxes and insurance, based on 2% of the initial total capital costs, is included in the fixed O&M costs.

Variable O&M costs for the system include the cost of electrical losses to maintain the PCS and the battery during hot standby intervals.

An allowance for nickel-cadmium battery disposal costs is also included at the end of battery life, covering the cost of removing the battery from the plant. Batteries are usually accepted by manufacturers so that the active materials can be recovered and reused.

Lifecycle Benefit and Cost Analysis for Nickel-Cadmium Systems

Further insight to the value of energy storage can be gained through lifecycle cost analyses using a net present value (NPV) methodology and comparison with alternatives. The financial parameters in Table 7-3 are used to assess the applications described in the preceding sections.

Table 7-3
Financial Parameters

Dollar Value	2003
System Startup	June 2006
Project Life, years	20
Discount Rate (before tax), %	7.5
Property Taxes & Insurance, %/year	2
Fixed Charge Rate, %/year	9.81

The results of lifecycle cost benefit analyses of this application are summarized in Table 7-4 and discussed below. The bases and methodology used in valuing energy storage applications is described in detail in Chapter 4. The details of the benefit-cost analysis for each application are discussed below.

Table 7-4
Summary of Benefit and Cost Analyses of Nickel-Cadmium Systems

	Single Function
Applications	App M: GFX - Grid Frequency Support
Alt Solution Value, $/kW	750
Initial Installed Cost, M$	6.00
Total Costs, M$	(8.8)
Total Benefits, M$	7.5
Benefit to Cost Ratio	0.86
NPV, M$	(1.3)
Battery Type	Saft Pocket Plate SBH 920, 220-Module String
Number of Strings	2
Battery 2006 Price, K$/string	1,712
Battery Price for NPV=0, K$/string	1250

- Application M: Grid Frequency Support (GFX) – This application was evaluated on the assumption that an alternative system capable of mitigating GFX events can be obtained for capitalized acquisition and operating costs of about $750/kW, including acquisition, fixed and variable O&M, and property taxes and insurance costs. As shown in Table 7-4, this application yields a negative NPV of $(1.3) million for an initial investment of about $6.0 million on this basis. As a measure of the sensitivity of NPV with respect to alternative system costs, Figure 7-1 illustrates the change in NPV over a range of $500 to $1000/kW and shows that this nickel-cadmium system will compete favorably against alternative solutions with net capitalized costs in excess of about $875/kW. As an additional indicator of NPV sensitivity with respect to the cost of energy storage, if the price of the nickel-cadmium string were reduced from $1,712 thousand to $1,250 thousand per string, the NPV would equal zero, i.e., costs and benefits would be equal with those for alternative solutions valued at $750/kW.

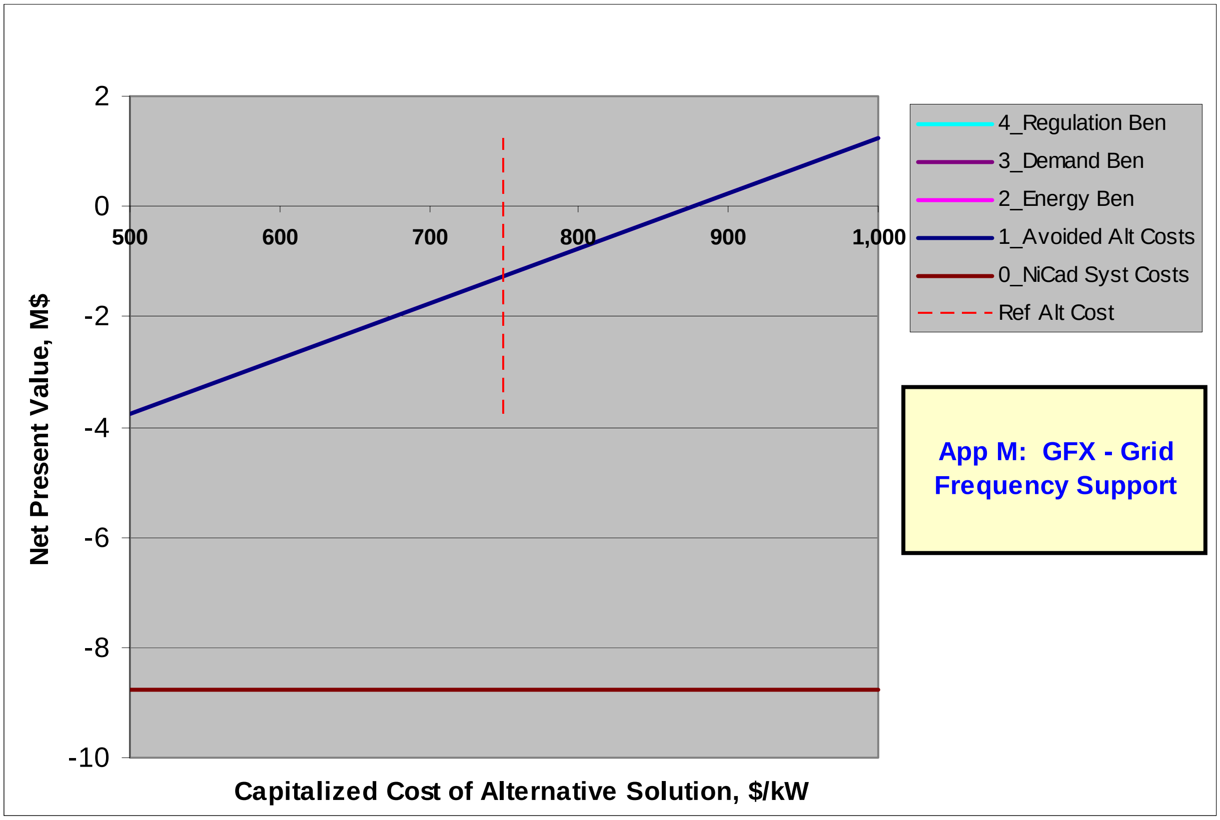

Figure 7-1
Application M: Nickel-Cadmium System NPV vs Cost of Alternative System

Interpreting Results From Benefit-Cost Analyses

In general, nickel-cadmium battery systems are expected to be competitive in GFX applications where the NPV of the alternative solution is in the range of about $850/kW.

The reader is reminded that the foregoing analyses are intended as a guide to the initial consideration of energy storage options, and that these analyses are based on representative electric rates and costs for alternative systems as described in Chapter 4. The assumptions used herein should be reviewed in light of project specific applications, alternative solutions, electric rates and financial parameters.

References

1. Communications with Jim McDowall of Saft, November, 2004.

8
SODIUM-SULFUR BATTERIES

Update Overview

During the past year since the issuance of the Handbook, NGK's commercial deployment of the sodium-sulfur (NAS) battery in Japan has continued to progress. Through September 2004, over 100 projects have been installed, including early demonstration projects back to 1992. For projects rated at 500 kW_{ac} or more, there are 55 operating projects with a cumulative nominal capacity of about 80 MW_{ac} and 625 MWh_{ac}. During 2004, the Tokyo Electric Power Company (TEPCO) has installed two 8 MW_{ac} projects each with about 60 MWh_{ac} at two of their industrial customers, the largest battery energy storage projects in the world [1].

In the U.S., the operation of the Gahanna project, hosted by the American Electric Power Company (AEP), continues with the completion of the two year demonstration and performance period in September. This project provides up to 500 kW_{ac} for 30 seconds of power quality plus 100 kW_{ac} of daily peak shaving for up to 7.2 hours. A final report on the overall experience and performance assessment has been prepared by AEP as part of an EPRI tailored collaboration project [2]. In addition, an independent assessment of the performance has also been completed, which was funded by DOE [3]. Overall, the Gahanna project provides a solid base of NAS battery experience for follow-on project developments by NGK in the U.S. and Europe.

Wind Power Application Experience

TEPCO and NGK have conducted two significant demonstration projects marrying wind with NAS energy storage. In December 1995, a proof-of-concept demonstration was begun at the TEPCO New Energy Park, in which a 50 kW_{ac} NAS battery was connected to a 300 kW_{ac} wind turbine. This demonstration was intended to explore the use of the NAS battery to provide fluctuation suppression for a wind turbine. The demonstration was considered a success, and a larger scale project was planned [4].

The opportunity for such a project came about in 2000 through the Institute of Applied Energy (IAE), a research foundation based in Tokyo and dedicated to finding system solutions to energy and environmental issues. IAE was commissioned by the New Energy and Industrial Technology Development Organization (NEDO), a Japanese government agency, to conduct a field study for the stabilization of output of wind turbines with storage batteries [5]. The resulting project proposed to investigate the use of energy storage to mitigate power fluctuations as a result of wind gusts.

Three projects were funded by NEDO through IAE, one of which was the installation of a NAS battery on the island of Hachijojima, about 300 km south of Tokyo. In the course of the project, a single 500 kW_{ac} wind turbine was stabilized through the installation and integration of a 400 kW_{ac} NAS battery. The battery was designed to provide power for 7 hours, allowing the system to be used for energy shifting as well as fluctuation suppression. Both operation modes were tested successfully in the demonstration project [4, 5].

Select Wind Applications for NAS Battery Systems

This section presents the select wind applications for which the NAS system is suited and describes the key features of the NAS systems when configured to meet the requirements of those applications. Screening economic analyses have shown that NAS battery systems are potentially competitive for one of the single function applications and all of the combined function applications described in detail in Chapter 3. The following list briefly summarizes and reiterates key requirements for all applications. Those for which NAS is best suited are enclosed by borders.

Single Function Applications

Application J: Transmission Curtailment (TC) – mitigation of power delivery constraint imposed by insufficient transmission capacity. Except for large CAES, reference duty cycle for analysis is derived from the reference 60 MW Texas wind farm profile constrained to 50 MW by available transmission capacity, valued at market electricity rates for the incremental wind generation and capacity delivered, plus the value of avoided T&D upgrade.

Application K: Time-Shifting (TS) – firms and shapes wind generation via the reference NREL wind profile by storing wind generation during the off-peak interval (6:00 pm to 6:00 am), supplemented by power purchased from the grid when wind generation is inadequate, and discharged during the on-peak interval (6:00 am to 6:00 pm). Valued at the market rates for the time-shifted, shaped energy and capacity; plus the value of avoided peaking generation upgrade.

Application L: Forecast Hedge (FH) – mitigates errors (shortfalls) in wind energy bid three hours prior to a one-hour delivery interval via the reference NREL wind profile. Valued at the incremental value of wind energy and capacity delivered at market rates and avoided penalties.

Application M: Grid Frequency Support (GFX) – supports grid frequency during sudden large decreases in wind generation and similar to GFS above, i.e., “prompt” spinning reserve (or load) for mitigating load-generation imbalance. Requires energy storage to discharge real power for durations up to 30 minutes. The reference duty cycle for analysis is standby for infrequent events characterized by 15 minute FPD, 1 event per day, 10 events per year. Valued at the cost of alternative solutions..

Application N: Fluctuation Suppression (FS) – stabilizes wind farm generation frequency by suppressing fluctuations (absorbing and discharging energy during short duration variations in output). Valued at the cost of alternative solutions.

Combined Function Applications (In the Order Noted)

Application C6:	Combined Applications J, M, D (TC + GFX + RC)
Application C7:	Combined Applications K, M, D (TS + GFX + RC)
Application C8:	Combined Applications L, M, D (FH + GFX + RC)
Application C9:	Combined Applications N, M, K (FS + GFX + TS)

NAS Battery System Compliance with Application Requirements

The NAS battery module performance parameters presented in the Handbook were used to develop approximate sizes and operational parameters for systems meeting the application requirements for the selected NAS wind applications described in the previous section. Key factors in sizing NAS systems include:

- Selection of the type of NAS module and pulse factor (which determines the minimum discharge voltage and therefore the PCS cost).
- State-of-charge (SOC) management to ensure that the required power and energy are accessible and that the battery is appropriately recharged. In particular, for the TC application, the minimum SOC is limited to 30%, which may be sustained for days, in order to ensure the expected lifetime performance characteristics.
- Thermal management to ensure that cell temperatures are maintained within the acceptable range and that the rate of heat loss is appropriate to the application (e.g., minimized for standby applications).
- Cycle life management to ensure that the system is operated within the service life of equipment, which is especially important for combined function, high cycle applications such as time shift with regulation control.

Performance aspects of NAS battery systems for the selected applications are described below and summarized in Table 8-1. The reference power for all applications is 10 MW_{ac}.

- Application L: Forecast Hedge (FH) – This application requires that the system supply stored energy to supplement wind generation upon demand and requires a prompt PCS. The minimum discharge voltage is 930 V_{dc}. The system is comprised of two hundred (200) NAS G50 Modules capable of discharging at a pulse factor of 1 (i.e., 50 kW_{ac} per module) for up to 7.2 hours and a Type I PCS. The G50 Module design allows heat loss at a rate of 3.4 kW_{ac} per module, resulting in the NAS system standby efficiency of 96.1%. The projected battery life for this application is 15 years, since cycle life (as measured by the cumulative cycle fraction of 71% at 90% DOD) exceeds shelf life.

Table 8-1
NAS Battery System Compliance with Application Requirements

Applications	Single Function	Combined Functions			
	App L: FH - Forecast Hedge, NREL Wind	**App C6: TC + GFX + RC**	**App C7: TS + GFX + RC**	**App C8: FH + GFX + RC**	**App C9: FS + GFX + TS**
Battery Selection					
Type of Modules	G50	E50	E50	G50	E50
Number of Modules	200	200	200	200	200
Pulse Factor	1.0	1.0	1.0	1.0	1.0
Max Charge Voltage	1,550	1,550	1,550	1,550	1,550
Min Discharge Voltage	930	930	930	930	930
Maximum DOD, %	90%	70%	90%	90%	90%
Cumulative Cycle Fraction	71%	100%	100%	100%	97%
Replacement Interval, yr	15	15	10	10	13
PCS Selection					
PCS Type (Chapter 5)	I	I	I	I	I
Duty Cycles					
Grid Support or Power Quality (GS or PQ)					
Power, MW		10	10	10	10
Event Duration, Hr		0.25	0.25	0.25	0.25
Generation Shifting (TC, TS or FH)					
Power, MW	10.0	10.0	10.0	10.0	8.0
Generation Shift Energy, MWh/yr	16,831	10,116	28,291	16,831	26,883
Cycle Life Fraction	71%	48%	74%	47%	97%
Regulation Control (RC)					
Power, MW		10.0	10.0	10.0	
Hours per day, hr		20	20	20	
Days per year, days		260	195	335	
RC, MW-Hours/yr		52,000	39,000	67,000	
RC Losses, MWh/yr		3,946	2,960	5,085	
Cycle Life Fraction		51%	26%	53%	
Summary System Data					
Standby Hours per Year	5,057	1,334	0	0	0
System Net Efficiency, % (See Note)	89.1%	90.6%	86.8%	88.4%	90.7%
NAS Standby Efficiency, %	96.1%	99.0%	100.0%	100.0%	100.0%
PCS Standby Efficiency, %	98.8%	99.7%	100.0%	100.0%	100.0%
System Footprint, MW/sqft (MW/m^2)	0.0014 (0.0152)	0.0014 (0.0152)	0.0014 (0.0152)	0.0014 (0.0152)	0.0014 (0.0152)
NAS Footprint, MW/sqft (MW/m^2)	0.0017 (0.0185)	0.0017 (0.0185)	0.0017 (0.0185)	0.0017 (0.0185)	0.0017 (0.0185)

Note: System net efficiency includes losses for energy conversion and system standby expressed on an annual basis, i.e., one minus inefficiency, where inefficiency equals the ratio of annual energy losses to the product of system rated power times 8760 hours, expressed in percent.

- Application C6: Combined Applications J, M, D (TC + GFX + RC) – This application requires that the system store energy when wind generation exceeds transmission capacity, plus continuously be able to provide GFX up to once a day. Two hundred (200) NAS E50 Modules capable of discharging at 50 kW_{ac} per module for up to 8.6 hours are equipped with a Type I PCS for prompt response to GFX events. For this application, the energy storage system is required to spend several hundred hours at a low-state-of-charge in order to capture wind generation in excess of transmission capacity when called upon. The minimum state of charge for extended periods is limited to 30% for NAS batteries. In addition, this system will provide RC functions at a power of 10 MW_{ac} for 20 hours per day and is available for such 260 days per year. (The large number of cycles is acceptable because the depth-of-discharge for each cycle is only about 1.7%.) Because of the essentially continuous duty cycle associated with RC, the NAS system employs modules designed to allow heat loss at a rate of 3.4 kW_{ac} per module, resulting in the NAS standby efficiency of 99.0%. The projected battery life for this application is 15 years, since cycle life equals the shelf life (i.e., the cumulative damage fraction is 100% at 70% DOD).
- Application C7: Combined Applications K, M, D (TS + GFX + RC) – This application requires that the system store wind generated or purchased energy during the off-peak period for discharge during the on-peak period, plus continuously detect events lasting up to 15 minutes for GFX. Two hundred (200) NAS E50 Modules capable of discharging at 50 kW_{ac} per module for up to 8.6 hours are equipped with a Type I PCS for prompt response to GFX events. In addition, this system will provide RC functions at a power of 10 MW_{ac} for 20 hours per day, 195 equivalent days per year. Because of the essentially continuous duty cycle associated with these combined functions, the NAS system employs modules designed to allow heat loss at a rate of 3.4 kW_{ac} per module, resulting in the NAS standby efficiency of 100% (essentially, no time in standby mode). Because of these high cycle functions, the projected battery life for this application is 10 years (i.e., the cumulative damage fraction is 100% at 90% DOD over a 10-yr period).
- Application C8: Combined Applications L, M, D (FH + GFX + RC) – This application requires that the system store wind generated in excess of the bid amount, and/or purchased energy during the off-peak period, for use in mitigating shortfalls in the 3-hour ahead bid forecast market , plus continuously detect events lasting up to 15 minutes for GFX. Two hundred (200) NAS G50 Modules capable of discharging at 50 kW_{ac} per module for up to 7.2 hours are equipped with a Type I PCS for prompt response to GFX events. In addition, this system will provide RC functions at a power of 10 MW_{ac} for 20 hours per day, 335 equivalent days per year. Because of the essentially continuous duty cycle associated with these combined functions, the NAS system employs modules designed to allow heat loss at a rate of 3.4 kW_{ac} per module, resulting in the NAS standby efficiency of 100% (essentially, no time in standby mode). Because of these high cycle functions, the projected battery life for this application is 10 years (i.e., the cumulative damage fraction is 100% at 90% DOD over a 10-yr period).
- Application C9: Combined Applications N, M, K (FS + GFX + TS) – This application requires that the system serve as a varying load at night to absorb the power fluctuations and a varying source during the day to compensate the fluctuations, such that fluctuations are suppressed for grid access. In addition, the system stores wind generated or purchased energy during the off-peak period for discharge during the on-peak period, plus continuously

detects events lasting up to 15 minutes for GFX. Two hundred (200) NAS E50 Modules capable of discharging at 50 kW_{ac} per module for up to 8.6 hours are equipped with a Type I PCS for prompt response to GFX events. Because of the essentially continuous duty cycle associated with these combined functions, the NAS system employs modules designed to allow heat loss at a rate of 3.4 kW_{ac} per module, resulting in the NAS standby efficiency of 100% (essentially, no time in standby mode). Because of these high cycle functions, the projected battery life for this application is 13 years (i.e., the cumulative damage fraction is 97% at 90% DOD over a 13-yr period).

Benefit and Cost Analyses

NAS Battery Pricing and Integrated System Costs

Since April 2003, NGK and TEPCO have established the full commercialization of the NAS battery in Japan, including commercial-scale manufacturing facilities, firm prices, commercial warranties and full service options. Market introduction for North America is underway through the development of select high value demonstration projects. Current nominal unit prices for utility scale applications in North America are in the range of $85K to $95K per module, depending on module type, number of modules, site location, etc. For the Handbook’s reference deployment date of 2006 and rating of 10MW_{ac}, nominal unit prices are based on NGK’s planned expansion of their manufacturing capacity. For any replacement modules over the assumed 20 year project lifetimes, fully mature price estimates are applied. The resultant NAS PQ and PS module prices applied for the benefit-cost assessments herein are:

NAS Module	2006 Prices, K$	Mature Prices, K$
E50	$75	$55
G50	$68	$50
PQ50	$75	$55

In addition to the NAS battery modules, the related NAS scope of supply includes the battery management system, DC circuit breakers (PQ modules only), exterior enclosures, import duties and fees, shipment from Japan to an inland site, plus technical support for system integration, installation and startup.

The cost of integrated NAS systems is obtained by combining the cost of the NAS battery scope of supply with the appropriate PCS and BOP costs as described in Chapter 5 of the Handbook. The PCS and BOP costs shown in Table 8-2 are based on that methodology. Since the cost of exterior enclosures is included in the NAS battery scope of supply, the cost of exterior space and foundations for NAS batteries is included at $20/sqft.

Table 8-2
Capital and Operating Costs for NAS Battery Systems

Applications	Single Function	Combined Functions			
	App L: FH - Forecast Hedge, NREL Wind	App C6: TC + GFX + RC	App C7: TS + GFX + RC	App C8: FH + GFX + RC	App C9: FS + GFX + TS
NAS Battery Capacity, MWh_{ac}	65	60	78	65	86
PCS Initial Cost, $/kW	239	239	239	239	239
BOP Initial Cost, $/kW	100	100	100	100	100
NAS Battery Initial Cost, $/kW	1,382	1,523	1,523	1,382	1,523
NAS Battery Initial Cost, $/kWh	213	253	196	213	178
Total Capital Cost, M$	17.2	18.6	18.6	17.2	18.6
O&M Cost – Fixed, $/kW-year	39.4	42.2	42.2	39.4	42.2
O&M Cost– Variable, $/kW-year	16.9	4.5	0.0	0.0	0.0
NPV NAS Disposal Cost, $/kW	25.4	33.5	54.1	54.1	39.5

Note: The total initial cost may be calculated in two ways:
1. By mutiplying the sum of PCS, BOP and Battery initial costs expressed in $/kW by the reference power,
2. OR by mutiplying the sum of PCS and BOP expressed in $/kW by the reference power and then adding the product of Battery Initial cost expressed in $/kWh and the Battery Capacity

Fixed O&M costs for the PCS are based on $2/kW as required by provisions in Chapter 5 of the Handbook, plus NAS battery maintenance in accordance with the vendor. NGK's recommended maintenance program consists of continuous remote monitoring and detailed inspections conducted at 3-year intervals, which include:

- Inspecting for unusual vibrations, noise or odors
- Inspecting for abnormal conditions of connecting cables and the exterior enclosure
- Inspecting insulation resistance
- Retorquing terminal connections
- Collecting and analyzing battery resistance and OCV data
- Confirming the accuracy of DC voltage, DC current, and temperature sensors
- Adjusting module enclosure vacuum to control standby heat loss (every 1000 cycles)

Based on experience gained at TEPCO demonstration projects, the levelized annual labor for NAS battery installations of 20 modules and greater averages 3 hours per module. Fixed O&M costs are based on labor costs of $50 per hour (or $150 per module per year). In addition, an annual allowance for property taxes and insurance, based on 2% of the total initial capital costs, is included in the fixed O&M costs.

Variable O&M costs for the system include the cost of electrical losses to maintain the PCS during hot standby intervals and the NAS operating temperature regime. An allowance for NAS battery disposal costs is included at $3,750 per module at the end of battery life, including the cost of recycling useable material and disposition of sodium residuals.

Lifecycle Benefit and Cost Analysis for NAS Battery Systems

Further insight to the value of energy storage can be gained through lifecycle cost analyses using a net present value (NPV) methodology and comparison with alternatives. For the convenience of the reader, the financial parameters set forth in the Handbook and used in the analyses of this Supplement are summarized in Table 8-3.

Table 8-3
Financial Parameters

Dollar Value	2003
System Startup	June 2006
Project Life, years	20
Discount Rate (before tax), %	7.5
Property Taxes & Insurance, %/year	2
Fixed Charge Rate, %/year	9.81

The results of lifecycle cost benefit analyses of select NAS battery applications are summarized in Table 8-4 and discussed below. The bases and methodology used in valuing energy storage applications are described in detail in Chapter 4. The details of the benefit-cost analysis for each application are discussed below.

Table 8-4
Summary of Benefit and Cost Analyses of NAS Battery Systems

Applications	Single Function	Combined Functions			
	App L: FH - Forecast Hedge, NREL Wind	App C6: TC + GFX + RC	App C7: TS + GFX + RC	App C8: FH + GFX + RC	App C9: FS + GFX + TS
Alt Solution Value, $/kW	0	1,500	750	750	1,500
Initial Installed Cost, M$	17.22	18.62	18.62	17.22	18.62
Total Costs, M$	(24.8)	(25.4)	(28.8)	(26.6)	(26.1)
Total Benefits, M$	23.3	22.6	29.6	39.7	30.8
Benefit to Cost Ratio	0.94	0.89	1.03	1.49	1.18
NPV, M$	(1.5)	(2.9)	0.8	13.1	4.7
NAS Module	G50	E50	E50	G50	E50
Number of Modules	200	200	200	200	200
NAS 2006 Price, K$/module	68	75	75	68	75
NAS Price for NPV=0, K$/module	62	63	78	122	95

- Application L: Forecast Hedging (FH) – This application was evaluated on the basis of avoided risks associated with market rates and penalties for wind generation bid into the 3-hour ahead market electricity market as described in Chapters 3 and 4. As shown in Table 8-4, this application yields a negative NPV of ($1.5) million for an initial investment of about $17.2 million on this basis. As an indicator of NPV sensitivity with respect to the cost of energy storage, if the price of NAS G50 modules were decreased from $68,000 to $62,000 per module, the NPV would equal zero, i.e., costs and benefits would be equal.

- Application C6: Combined Applications J, M, D (TC + GFX + RC) – This application was evaluated on the assumption that an alternative solution capable of mitigating TC events, plus avoided GFX related upgrade costs, can be obtained for net capitalized costs of about \$1500/kW, including acquisition, fixed and variable O&M, and property taxes and insurance costs. As shown in Table 8-4, this application yields a negative NPV of (\$2.9) million for an initial investment of about \$18.6 million on this basis. As a measure of the sensitivity of NPV with respect to alternative solution costs, Figure 8-1 illustrates the change in NPV over a range of \$1000 to \$2000/kW, as well as the incremental value of regulation control. With these value elements, NAS systems will compete favorably against alternative solutions valued at more than about \$1780/kW. As an additional indicator of NPV sensitivity with respect to the cost of energy storage, if the price of NAS E50 modules were decreased from \$75,000 to \$63,000 per module, the NPV would equal zero, i.e., costs and benefits would be equal with those for alternative solutions valued at \$1500/kW.

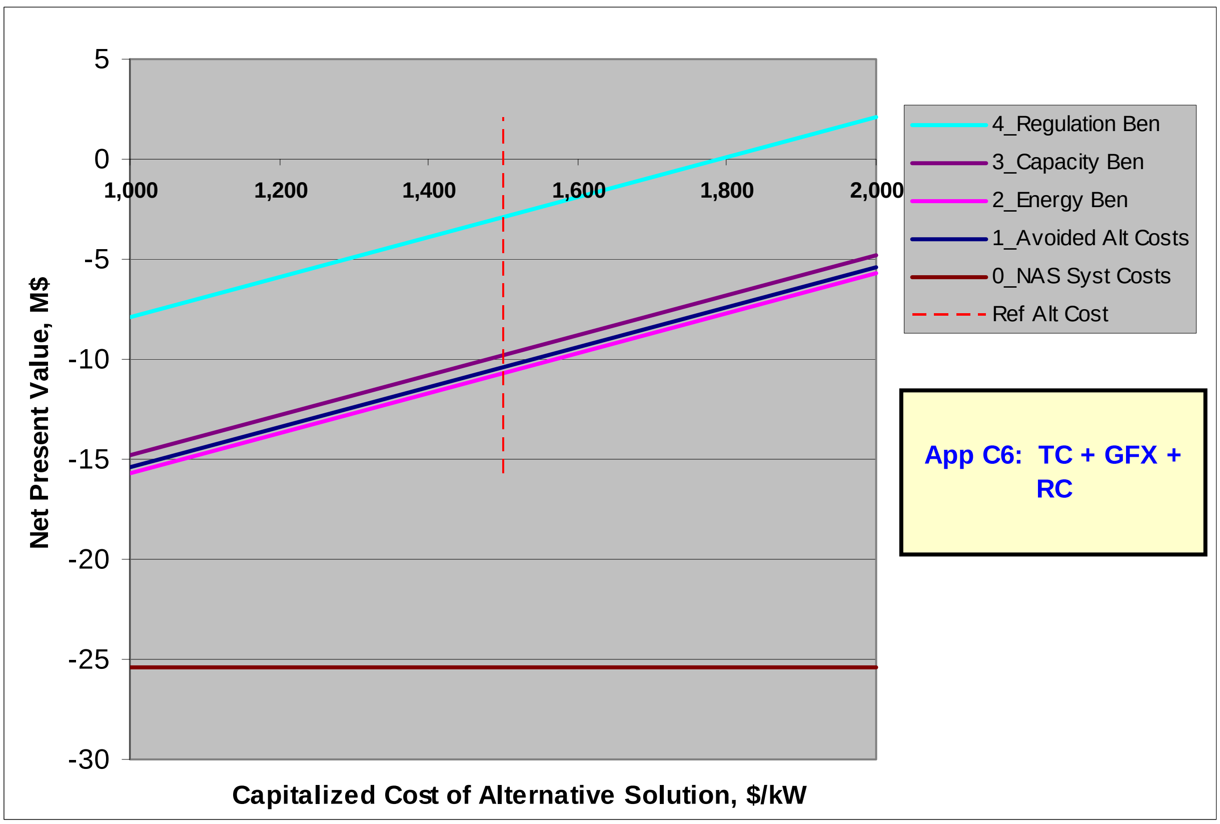

Figure 8-1
Application C6: NAS System NPV vs Cost of Alternative Solution

- Application C7: Combined Applications K, M, D (TS + GFX + RC) –This application was evaluated on the assumption that an alternative solution capable of acquiring on-peak generation at market rates, plus avoiding GFX related upgrade costs, can be obtained for net capitalized costs of about $750/kW, including acquisition, fixed and variable O&M, and property taxes and insurance costs. As shown in Table 8-4, this application yields a NPV of $0.8 million for an initial investment of about $18.6 million on this basis. As a measure of the sensitivity of NPV with respect to alternative solution costs, Figure 8-2 illustrates the change in NPV over a range of $500 to $1000/kW, as well as the incremental value of regulation control. With these value elements, NAS systems will compete favorably against alternative solutions valued at more than about $680/kW. As an additional indicator of NPV sensitivity with respect to the cost of energy storage, if the price of NAS E50 modules were increased from $75,000 to $78,000 per module, the NPV would equal zero, i.e., costs and benefits would be equal with those for alternative solutions valued at $750/kW.

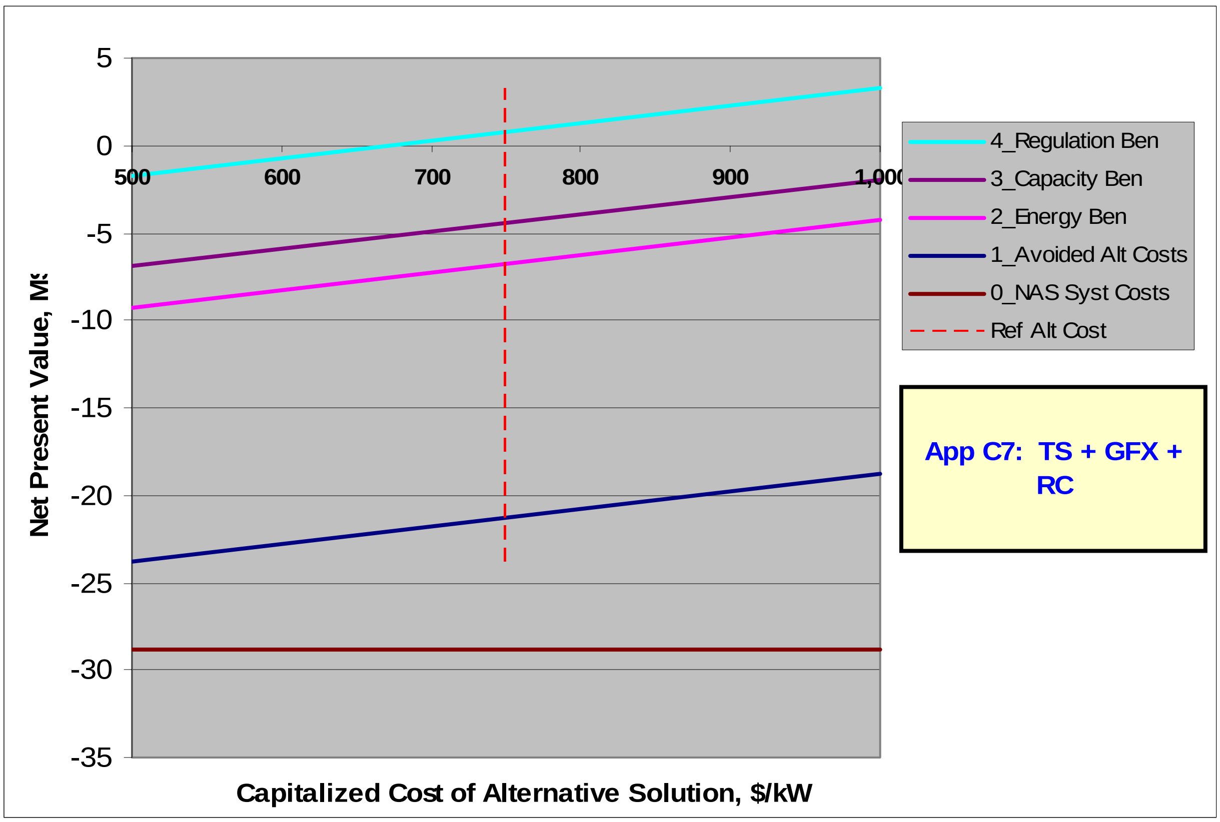

Figure 8-2
Application C7: NAS System NPV vs Cost of Alternative Solution

- Application C8: Combined Applications L, M, D (FH + GFX + RC) – This application was evaluated on the basis of avoided risks associated with market rates and penalties for wind generation bid into the 3-hour ahead market electricity market as described in Chapters 3 and 4, plus the assumption that avoided GFX related upgrade costs can be obtained for net capitalized costs of about $750/kW, including acquisition, fixed and variable O&M, and property taxes and insurance costs. As shown in Table 8-4, this application yields a NPV of $13.1 million for an initial investment of about $17.2 million on this basis. As a measure of the sensitivity of NPV with respect to alternative solution costs, Figure 8-3 illustrates the change in NPV over a range of $500 to $1000/kW, as well as the incremental value of regulation control. With these value elements, NAS systems will compete favorably against alternative solutions over this entire range. As an additional indicator of NPV sensitivity with respect to the cost of energy storage, if the price of NAS G50 modules were increased from $75,000 to $122,000 per module, the NPV would equal zero, i.e., costs and benefits would be equal with those for alternative solutions valued at $750/kW.

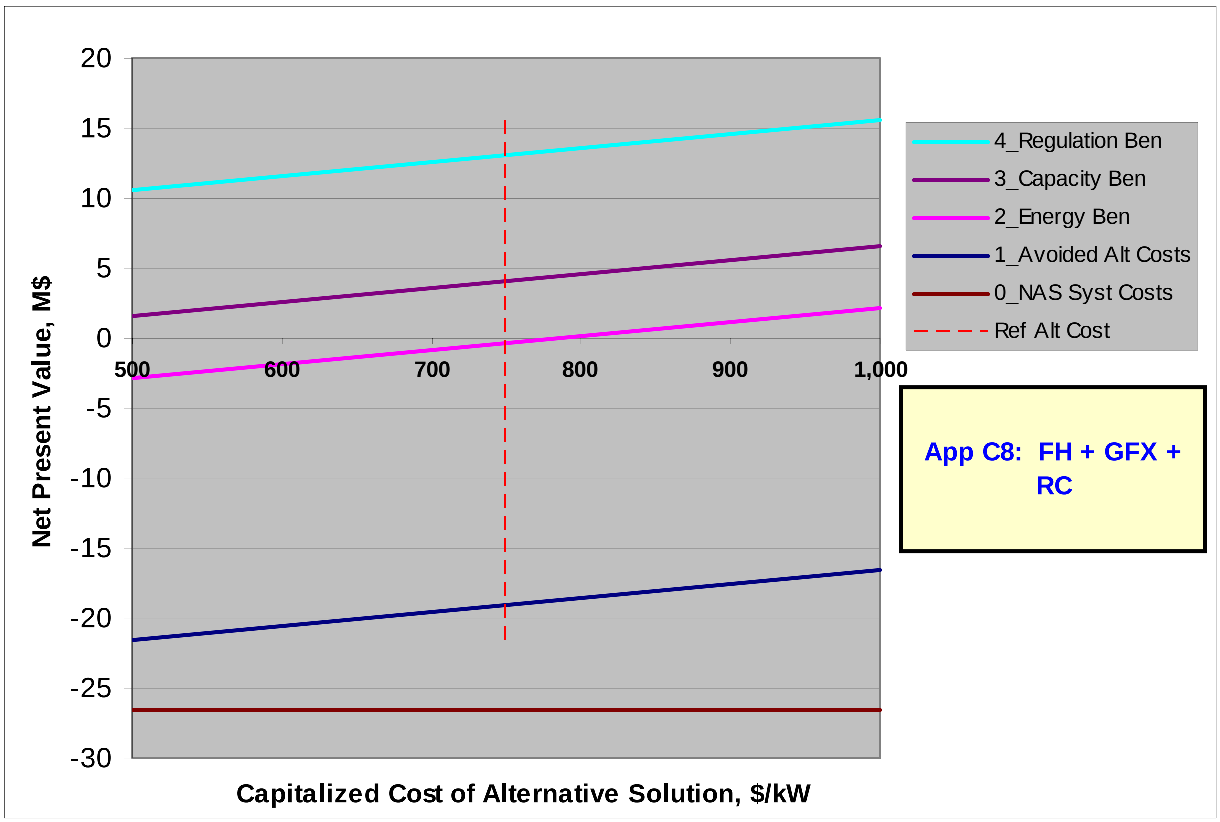

Figure 8-3
Application C8: NAS System NPV vs Cost of Alternative Solution

- Application C9: Combined Applications N, M, K (FS +GFX + TS) – This application was evaluated on the assumption that an alternative solution capable of suppressing 2 MW fluctuations from 12 MW wind farm, plus avoided GFX related upgrade costs, can be obtained for net capitalized costs of about $1500/kW, including acquisition, fixed and variable O&M, and property taxes and insurance costs. As shown in Table 8-4, this application yields an NPV of $4.7 million for an initial investment of about $18.6 million on this basis. As a measure of the sensitivity of NPV with respect to alternative solution costs, Figure 8-4 illustrates the change in NPV over a range of $1000 to $2000/kW, as well as the incremental value of time-shifting wind generation at market rates. With these value elements, NAS systems will compete favorably against alternative solutions valued at more than about $1050/kW. As an additional indicator of NPV sensitivity with respect to the cost of energy storage, if the price of NAS E50 modules were increased from $75,000 to $95,000 per module, the NPV would equal zero, i.e., costs and benefits would be equal with those for alternative solutions valued at $1500/kW.

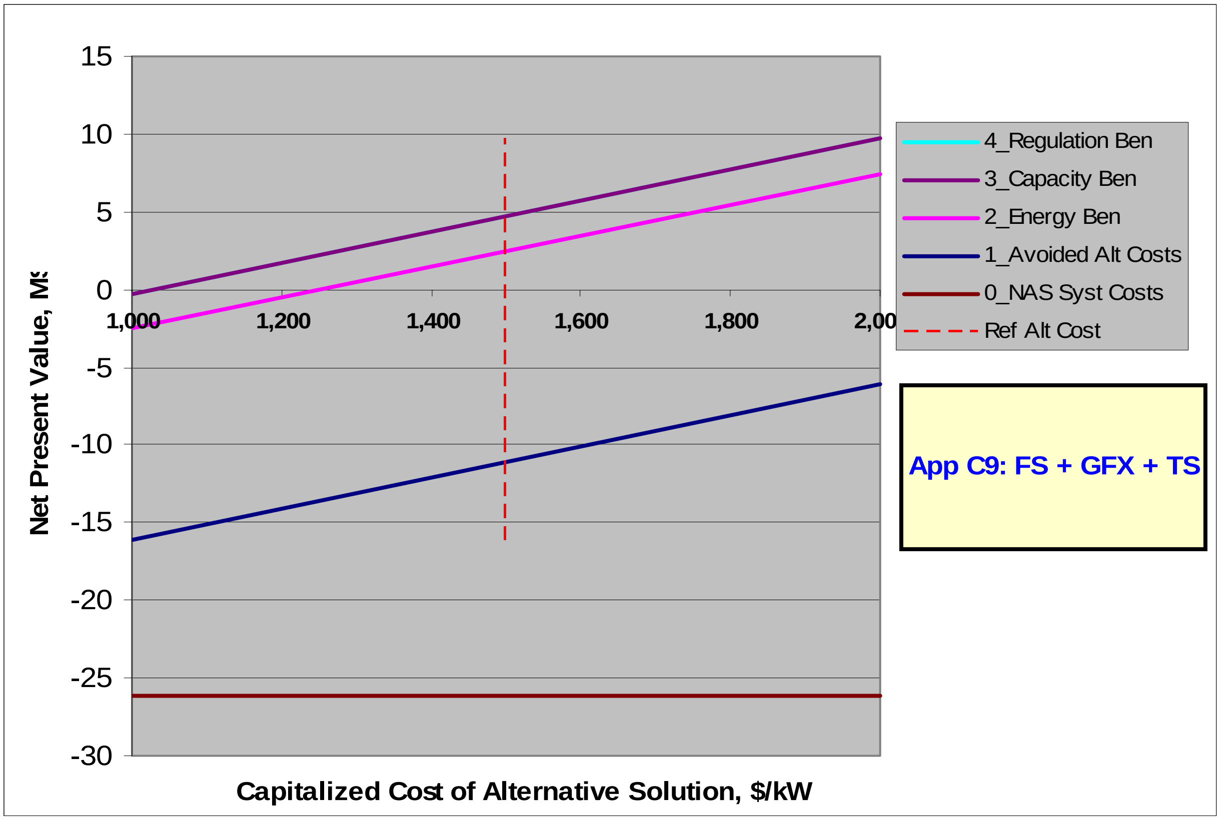

Figure 8-4
Application C9: NAS System NPV vs Cost of Alternative Solution

Interpreting Results from Benefit-Cost Analyses

The cost and performance of the NAS battery system is marginally competitive for single function FH applications. For the TC application, energy storage requirements are beyond the cost effective use of the product designs. Consequently, TC applications combined with GFX and RC (C6) are required even for marginal competitiveness. The NAS system is progressively breakeven to attractive over the range of value parameters for the combined function applications of C7, C9 and C8.

The reader is reminded that the foregoing analyses are intended as a guide to the initial consideration of energy storage options, and that these analyses are based on representative electric rates and costs for alternative solutions as described in Chapter 4. The assumptions used herein should be reviewed in light of project specific applications, alternative solutions, electric rates and financial parameters.

References

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3. Norris, B. L. - Gridwise Engineering Co., Newmiller, J. - Endecon Engineering, "Analysis of the NAS Battery Demonstration at American Electric Power", DOE/SNL report expected in February 2005.

4. International Electric Research Exchange, IERE (http://www-iere.dcc.co.jp/)

5. NEDO Press Release, September 7, 2000.

9
ZINC-BROMINE BATTERIES

Update Overview

Zinc-bromine batteries have seen continued development activity in the past year. On July 1st, 2004, the major developer of zinc-bromine products, ZBB Energy Corporation, began full-scale commercial operations, producing commercial zinc-bromine products with an automated manufacturing line. The products are going towards new zinc-bromine projects, including a project cofunded as part of a joint initiative between the Department of Energy (DOE) and the California Energy Commission (CEC). The CEC/DOE project will consist of four 500 kWac / 500 kWhac trailer-mounted ZBB battery systems, installed in series, resulting in a 2000 kWac / 2000 kWhac battery storage system. The project is a proof-of-concept installation in a load-shifting application for the purpose of distribution upgrade deferral. The modules are currently in production, and the installation is projected to be commissioned in October 2005.

In early 2004, Halcyon Energy, an Australian developer of zinc-bromine technology based in Brisbane, Queensland, was awarded two projects together worth A$300,000 to develop its zinc-bromine technology for remote power applications. Halcyon has so far concentrated on relatively small products for applications such as telecommunications backup power, and is not presently developing products for transmission and distribution applications.

Wind Power Application Experience

Zinc-bromine batteries have been investigated for wind applications in the past [1], but these programs have not seen any hardware demonstrations or testing to date. At present, however, no major zinc-bromine developers have plans to develop products or applications for wind power at this time.

Although zinc-bromine technology could be used in wind power applications in the future, no zinc-bromine products currently on the market appear to be suitable for the wind-related applications examined in this Supplement. Zinc-bromine products have been tested for up to 2000 cycles, or about 6000 hours, in several applications, but most wind-related applications require much longer cycle life for economic operation. For this reason, zinc-bromine products are not considered in the economic analyses in this Supplement.

References

1. B. Norris, R.Parry, R. M. Hudson. "An Evaluation of Windfarm Stabilization and Load Shifting Using the Zinc-Bromine Battery (ZBB)", Presented at WindPower 2002, June 2 to 5, 2002.

2. Communication with Peter Lex of ZBB Energy Corporation, November 2, 2004.

10
VANADIUM REDOX BATTERIES

Update Overview

During the past year, PacifiCorp formally announced the completion and operation of the Vanadium Redox Battery Energy Storage System (VRB-ESS) at its facility in Castle Valley, Utah at a ceremony held in March. Designed to provide voltage support and peak load relief to this remote area served by a 209 mile distribution feeder, the energy store has now operated for over 5000 hours and successfully fulfilled its intended purposes through a summer peak season. In early fall, the power conditioning system was upgraded to deliver up to 350 kVA, providing additional voltage support and real power capabilities. A cell upgrade is planned by the end of the year to boost the nominal capacity to 300kW_{ac} [1].

VRB Power's Australian subsidiary, Pinnacle VRB Ltd., continued to support the operation of its 800 kWh_{ac} installation on King Island, Australia, which provides load balancing, output smoothing, and reserve power requirements to the hybrid wind/diesel generating plant that serves the island (more below). In the third quarter, Pinnacle and VRB Power reached agreement on the transfer of all VRB technology patents (except those patents registered in Australia) to the parent company [1].

In September, VRB Power acquired an exclusive global license to the intellectual property and all remaining physical assets and inventory of the Regenesys electricity storage technology from RWE npower PLC, subsidiary of German based parent company RWE AG. This acquisition provides VRB Power with key manufacturing know-how and equipment for the assembly of cell stacks utilizing the VRB technology immediately and the Regenesys technology in the future. Concurrently, VRB Power engaged the services of the former Electrosynthesis Corp., who had been the in-house research arm of Regenesys based in the Buffalo, NY area, to continue the development of the Regenesys technology as well as enhancements to the VRB technology [1].

Sumitomo Electric Industries, Ltd. (SEI) has been manufacturing and marketing commercial VRB systems since 2000 and has commercial sales of MW-scale systems in Japan. In 2004, SEI entered into a technology transfer and license agreement with Reliable Power Inc. (Arlington, Virginia). Under this agreement, Reliable Power has exclusive license to all of SEI's VRB patents and technical know-how for North America and is licensed to manufacture VRB products in North America for sale worldwide, excluding Japan [2].

Wind Power Application Experience

Because of its potential for both short and long-duration energy storage, VRB has been considered for several wind-related applications. The first application of VRB to this application was led by the Institute of Applied Energy (IAE), a research foundation based in Tokyo and dedicated to finding system solutions to energy and environmental issues. In 2000, IAE was commissioned by the New Energy and Industrial Technology Development Organization (NEDO), a Japanese government agency, to conduct a field study for the stabilization of output of wind turbines with storage batteries [3]. The resulting project proposed to investigate the use of energy storage to mitigate power fluctuations as a result of wind gusts.

Three projects were funded by NEDO through IAE, one of which was the installation of a VRB system at the Horikappu Power Plant operated by Hokkaido Electric Power and located near Tomamae in Hokkaido, Japan. The VRB system was supplied by SEI and sized to provide 170 kW_{ac} for 6 hours and paired with a single 250 kW_{ac} wind turbine. The battery entered service in March 2001, and was used for two purposes: to stabilize the wind turbine output, and to store wind turbine power during periods of low demand and releasing it during periods of high demand.

A similar installation was placed on King Island, Australia by Pinnacle VRB (a subsidiary of VRB Power Systems) in 2003. King Island is a small island located between Australia and Tasmania, with a population of about 1,500 and a peak power load of about 3 MW_{ac}. At the time the King Island project was originally conceived, about 18% of this load was serviced by three 250 kW_{ac} Nordex wind turbines, with the balance provided by a diesel power station. HydroTasmania, the local utility, found that the wind turbines caused considerable fluctuations on the King Island grid, and explored various ways of mitigating these fluctuations before finally settling on an energy storage system. In 2003, the utility acquired funding from the Australian Greenhouse Office, an Australian government agency, to expand the wind farm on King Island with two 850 kW Vestas wind turbines and Pinnacle VRB's 200 kW Vanadium Redox flow battery. The VRB system contains six stacks produced by SEI, with the capability of delivering 200 kW_{ac} for four hours and a peak power capability of 400 kW_{ac} for 10 seconds. Although the battery was originally intended for both fluctuation stabilization and energy shifting, it is now used predominantly for the latter application [4].

Building on these successes, J-Power, a major Japanese generation utility, announced in 2003 that it would install a new VRB system at its Tomamae Wind Villa wind farm at Tomamae, Hokkaido. The VRB system has been supplied by SEI. The Wind Villa site consists of 19 wind turbines with a total output of 30.6 MW_{ac}. The VRB system was chosen in part because of its independence of power and energy sizing. Based on their simulation model, the battery has been sized for 6000 kW_{ac} for 20 minutes and 4000 kW_{ac} for 1.5 hours, with an inverter capability of 6000 kVA. Power output stabilization over the range of several seconds to several tens of minutes is the focus of this project. Field test results will be compared to the simulation model to evaluate the accuracy of the model and applicability to other wind farm sites. The Wind Villa VRB battery is slated to be commissioned by early 2005, and will operate until 2008 [5, 6]. It is the first commercial-scale demonstration of energy storage for grid connected wind power enhancement.

In addition to these projects, a study for the potential use of the VRB system is currently underway based upon wind energy production from the Foote Creek Rim facility in Carbon County, Wyoming. With an average wind speed of over 25 miles per hour, Foote Creek Rim stands on one of the best wind power sites in the contiguous U.S. The site now has 183 turbines, with a total generating capacity of 134.7 MW_{ac}. The site suffers, however, from severe transmission constraints at certain times, forcing wind curtailment. The study, conducted by SAIC with funding from the U.S. Department of Energy, is investigating the use of VRB technology to store the energy generated during times of transmission constraint and release it when transmission is not constrained, thereby increasing the export of green power to the Pacific Northwest. The resultant analyses methodology and recommendations are expected to be applicable to other wind projects as well. VRB technology was chosen for a number of reasons, including the independence of energy and power, the relatively quick response time, the high efficiency, and the positive experience with VRB technology at the Moab, Utah facility [7].

Select Wind Applications for VRB Battery Systems

This section presents select wind applications for which VRB batteries are suited and describes the key features of VRB systems configured to meet the requirements of such applications. Screening economic analyses have shown that VRB battery systems are potentially competitive for all of the combined function applications, which are described in detail in Chapter 3. The following list briefly summarizes all of the Chapter 3 applications, with a reiteration of the key application requirements. Those for which VRB batteries are best suited are enclosed with borders.

Single Function Applications

Application J: Transmission Curtailment (TC) – mitigation of power delivery constraint imposed by insufficient transmission capacity. Except for large CAES, reference duty cycle for analysis is derived from the reference 60 MW Texas wind farm profile constrained to 50 MW by available transmission capacity, valued at market electricity rates for the incremental wind generation and capacity delivered, plus the value of avoided T&D upgrade.

Application K: Time-Shifting (TS) – firms and shapes wind generation via the reference NREL wind profile by storing wind generation during the off-peak interval (6:00 pm to 6:00 am), supplemented by power purchased from the grid when wind generation is inadequate, and discharged during the on-peak interval (6:00 am to 6:00 pm). Valued at the market rates for the time-shifted, shaped energy and capacity; plus the value of avoided peaking generation upgrade.

Application L: Forecast Hedge (FH) – mitigates errors (shortfalls) in wind energy bid three hours prior to a one-hour delivery interval via the reference NREL wind profile. Valued at the incremental value of wind energy and capacity delivered at market rates and avoided penalties.

Application M: Grid Frequency Support (GFX) – supports grid frequency during sudden large decreases in wind generation and similar to GFS above, i.e., “prompt” spinning reserve (or load) for mitigating load-generation imbalance. Requires energy storage to discharge real power for durations up to 30 minutes. The reference duty cycle for analysis is standby for infrequent events characterized by 15 minute FPD, 1 event per day, 10 events per year. Valued at the cost of alternative solutions.

Application N: Fluctuation Suppression (FS) – stabilizes wind farm generation frequency by suppressing fluctuations (absorbing and discharging energy during short duration variations in output). Valued at the cost of alternative solutions.

Combined Function Applications (In the Order Noted)

Application C6: Combined Applications J, M, D (TC + GFX + RC)

Application C7: Combined Applications K, M, D (TS + GFX + RC)

Application C8: Combined Applications L, M, D (FH + GFX + RC)

Application C9: Combined Applications N, M, K (FS + GFX + TS)

VRB System Compliance with Application Requirements

The VRB battery plant[1] performance parameters discussed in previous sections were used to develop approximate sizes and operational parameters for systems meeting the application requirements of the selected applications listed above. Key factors in sizing VRB systems include:

- Selection of the optimal amount of stored energy for the application duty cycle under consideration, i.e., the cost effective volume of liquid electrolyte.
- State-of-charge management to ensure that the required power and energy are accessible and that the battery is appropriately recharged for the duty cycle.
- Flow rate management to ensure the capability to deliver stored energy efficiently, e.g., minimal flow is required during standby while higher flow rates may be appropriate for applications requiring prompt response.
- Selection of the optimal battery string voltage for the application, i.e., higher voltages generally allow lower PCS costs but cause higher shunt current losses which, depending upon the duty cycle, may be economically significant.
- Selection of the appropriate pulse factor for the application, i.e., pulse capability depends on both state-of-charge and flow rate, and maintaining high states of charge and flow rates can increase standby losses and limit duty cycle options.

Performance aspects of VRB battery systems for the selected applications are summarized in Table 10-1. The reference power for all applications is 10 MW_{ac}. VRB battery plants nominally rated for 6-, 9- and 10-hour discharges are designated VRB-6h, VRB-9h and VRB-10h, respectively. In consultation with vendors, a voltage window of 600 to 300 V_{dc} has been selected for the applications considered herein. As discussed later, these relatively low values make it necessary to adapt the PCS cost methodology described in Chapter 5 of the Handbook. Also, battery stacks are replaced at 10 years, and cycle life is not considered to be a limitation in

[1] Note that cost and performance data for VRB systems are presented for reference "plants" as opposed to individual modules as is done for some other technologies in this Handbook. This approach is used to accommodate vendor preferences on the content of disclosed information.

these analyses. The VRB system configurations for the selected applications are described below:

Table 10-1
VRB Battery System Compliance with Application Requirements

Applications	Combined Functions			
	App C6: TC + GFX + RC	App C7: TS + GFX + RC	App C8: FH + GFX + RC	App C9: FS + GFX + TS
Battery Selection				
VRB Battery Plant	VRB-10h	VRB-10h	VRB-6h	VRB-9h
Pulse Factor	1.0	1.0	1.0	1.0
Max Charge Voltage	600	600	600	600
Min Discharge Voltage	300	300	300	300
Maximum DOD, %	90%	90%	90%	100%
Replacement Interval, yr	10	10	10	10
PCS Selection				
PCS Type (Chapter 5) (See Note 1)	I	I	I	I
Duty Cycles				
Grid Support or Power Quality (GS or PQ)				
Power, MW	10	10	10	10
Event Duration, Hr	0.250	0.250	0.250	0.000
Generation Shifting (TC, TS or FH)				
Power, MW	10.0	10.0	10.0	8.0
Load Shift Energy, MWh/yr	11,664	31,627	16,349	25,312
Load Shift Losses, MWh/yr	4,491	12,178	6,295	9,746
Regulation Control (RC)				
Power, MW	10.0	10.0	10.0	
Hours per day, hr	20	20	20	
Days per year, days	350	350	350	
RC, MW-Hours/yr	70,000	70,000	70,000	
RC Losses, MWh/yr	6,738	6,738	6,738	
Summary System Data				
Standby Hours per Year	0	0	0	0
System Net Efficiency, % (See Note 2)	87.2%	78.4%	85.1%	88.9%
VRB Standby Efficiency, % (See Note 3)	100.0%	100.0%	100.0%	100.0%
PCS Standby Efficiency, %	100.0%	100.0%	100.0%	100.0%
System Footprint, MW/sqft (MW/m^2)	0.0007 (0.0078)	0.0007 (0.0078)	0.0007 (0.0078)	0.0007 (0.0078)
VRB Footprint, MW/sqft (MW/m2)	0.0008 (0.0086)	0.0008 (0.0086)	0.0008 (0.0086)	0.0008 (0.0086)

Notes:
1. PCS Type I costs are adjusted for continuous rating, see text
2. System net efficiency includes losses for energy conversion and system standby expressed on an annual basis, i.e., one minus inefficiency, where inefficiency equals the ratio of annual energy losses to the product of system rated power times 8760 hours, expressed in percent.
3. In consultation with vendors, a standby loss of 3.5% of nominal power has been assigned.

- Application C6: Combined Applications J, M, D (TC + GFX + RC) – This application requires that the system store energy when wind generation exceeds transmission capacity, plus continuously be able to provide GFX up to once a day. The VRB-10h system with minimum discharge voltage of 300 V_{dc} and pulse factor of 1.0 is equipped with a Type I PCS sized for the continuous rating of 10 MW_{ac}. In addition to mitigating TC and GFX events, this system will also provide regulation control at 10 MW_{ac} for 20 hours per day, 350 days per year. The VRB system spends essentially no time in standby mode, resulting in a standby efficiency of 100%.
- Application C7: Combined Applications K, M, D (TS + GFX + RC) – This application requires that the system store wind generated or purchased energy during the off-peak period for discharge during the on-peak period, plus continuously detect events lasting up to 15 minutes for GFX. The VRB-10h system with minimum discharge voltage of 300 V_{dc} and pulse factor of 1.0 is equipped with a Type I PCS sized for the continuous rating of 10 MW_{ac}. In addition to providing TS and mitigating GFX events, this system will also provide regulation control at 10 MW_{ac} for 20 hours per day, 350 days per year. The VRB system spends essentially no time in standby mode, resulting in a standby efficiency of 100%.
- Application C8: Combined Applications L, M, D (FH + GFX + RC)) – This application requires that the system store wind generated in excess of the bid amount, and/or purchased energy during the off-peak period, for use in mitigating shortfalls in the 3-hour ahead bid forecast market , plus continuously detect events lasting up to 15 minutes for GFX. The VRB-6h system with minimum discharge voltage of 300 V_{dc} and pulse factor of 1.0 is equipped with a Type I PCS sized for the continuous rating of 10 MW_{ac}. In addition to providing FH and mitigating GFX events, this system will also provide regulation control at 10 MW_{ac} for 20 hours per day, 350 days per year. The VRB system spends essentially no time in standby mode, resulting in a standby efficiency of 100%.
- Application C9: Combined Applications N, M, K (FS + GFX + TS) – This application requires that the system serve as a varying load at night to absorb the power fluctuations and a varying source during the day to compensate the fluctuations, such that fluctuations are suppressed for grid access. In addition, the system stores wind generated or purchased energy during the off-peak period for discharge during the on-peak period, plus continuously detects events lasting up to 15 minutes for GFX. The VRB-9h system with minimum discharge voltage of 300 V_{dc} and pulse factor of 1.0 $_{is}$ equipped with a Type I PCS sized for the continuous rating of 10 MW_{ac}. In addition to providing FS and mitigating GFX events, this system will also provide regulation control at 10 MW_{ac} for 20 hours per day, 350 days per year. The VRB system spends essentially no time in standby mode, resulting in a standby efficiency of 100%.

Benefit and Cost Analyses

VRB Battery Pricing and Integrated System Costs

VRB vendors have continued to make steady progress toward commercialization of product lines in the U.S., Japan and elsewhere. The cost and performance data shown herein were developed in consultation with such vendors and are deemed to be representative but, for a variety of market circumstances, these data are not directly associated with a specific vendor. For the reference deployment date of 2006 and power rating of 10 MW_{ac} used herein, nominal unit prices for the VRB battery scope of supply corresponding to a 10 MW_{ac} plant with 6-, 9- and 10-hour storage are as shown below[1] along with mature prices projected for 2010 and beyond.

VRB Plant	2006 Prices, K$	Mature Prices, K$
VRB-6h	$17,200	$12,600
VRB-9h	$18,600	$13,600
VRB-10h	$20,000	$14,600

The PCS and BOP costs shown in Table 10-2 are based on the methodology described in Chapter 5 of the Handbook, adapted slightly to accommodate the relatively low VRB discharge voltage (300 V_{dc}). PCS costs are based on Types I. In Table 10-2, initial costs include acquisition, space and installation costs; fixed O&M costs include projected annual costs for parts and labor, plus annual property taxes and insurance (based on 2% per year of the initial total capital costs); and variable O&M costs include standby losses and variable consumables. Environmental conditioning is included at $100/sqft in accordance with provisions in Chapter 5. In addition, battery stacks are replaced at 10 years at a cost of 50% of the mature price (cycle life is not considered to be a limitation). Disposal costs are deemed negligible and not included.

Fixed O&M costs for the PCS are based on $2/kW as required by provisions in Chapter 5 of the Handbook, plus VRB battery maintenance in accordance with vendor recommendations. Maintenance activities include:

- Confirming the operability of system protective devices
- Calibrating sensors and instrumentation
- Inspecting for unusual vibrations, noise or odors
- Inspecting for abnormal conditions of connecting cables and piping
- Inspecting insulation resistance
- Servicing the battery controller, pumps, fans, and other system components

Based on vendor input, annual fixed O&M costs for 8 labor-days at $50 per hours are included in the assessment.

[1] The reference energy storage capacity for leading emerging flow battery technologies is 10 hours. A representative price for VRB systems over the range of 8 to 12 hours storage can be obtained by applying increments/decrements at the rate of $150/kWh.

Table 10-2
Capital and Operating Costs for VRB Battery Systems

Applications	Combined Function			
	App C6: TC + GFX + RC	**App C7: TS + GFX + RC**	**App C8: FH + GFX + RC**	**App C9: FS + GFX + TS**
VRB Battery Capacity, MWhac	90	90	54	83
PCS Initial Cost, $/kW	466	466	466	466
BOP Initial Cost, $/kW	100	100	100	100
VRB Battery Initial Cost, $/kW	2,125	2,125	1,845	1,985
VRB Battery Initial Cost, $/kWh	236	236	342	240
Total Capital Cost, M$	26.9	26.9	24.1	25.5
O&M Cost – Fixed, $/kW-year	56.1	56.1	50.5	53.3

Note: The total initial cost may be calculated in two ways:
1. By mutiplying the sum of PCS, BOP and Battery initial costs expressed in $/kW by the reference power,
2. OR by mutiplying the sum of PCS and BOP expressed in $/kW by the reference power and then adding the product of Battery Initial cost expressed in $/kWh and the Battery Capacity

Lifecycle Benefit and Cost Analysis for VRB Battery Systems

Further insight to the value of energy storage can be gained through lifecycle cost analyses using a net present value (NPV) methodology and comparison with alternatives. For the convenience of the reader, the financial parameters set forth in Chapters 5 of the Handbook and used in the analyses are summarized in Table 10-3.

Table 10-3
Financial Parameters

Dollar Value	2003
System Startup	June 2006
Project Life, years	20
Discount Rate (before tax), %	7.5
Property Taxes & Insurance, %/year	2
Fixed Charge Rate, %/year	9.81

Table 10-4
Summary of Benefit and Cost Analyses of VRB Battery Systems

Applications	Combined Functions			
	App C6: TC + GFX + RC	App C7: TS + GFX + RC	App C8: FH + GFX + RC	App C9: FS + GFX + TS
Alt Solution Value, $/kW	1,500	750	750	1,500
Initial Installed Cost, M$	26.91	26.91	24.11	25.51
Total Costs, M$	(36.2)	(36.2)	(32.3)	(34.3)
Total Benefits, M$	36.1	33.8	38.3	28.8
Benefit to Cost Ratio	1.00	0.93	1.19	0.84
NPV, M$	(0.1)	(2.4)	6.0	(5.5)
VRB Plant Designation	VRB-10h	VRB-10h	VRB-6h	VRB-9h
VRB Plant 2006 Price, M$	20.0	20.0	17.2	18.6
VRB Price for NPV=0, M$	19.9	18.3	21.5	14.6

- Application C6: Combined Applications J, M, D (TC + GFX + RC) – This application was evaluated on the assumption that an alternative solution capable of mitigating TC events, plus avoided GFX related upgrade costs, can be obtained for net capitalized costs of about \$1500/kW, including acquisition, fixed and variable O&M, and property taxes and insurance costs. As shown in Table 10-4, this application yields an NPV of essentially zero (\$0.1 million) for an initial investment of about \$26.9 million on this basis. As a measure of the sensitivity of NPV with respect to alternative solution costs, Figure 10-1 illustrates the change in NPV over a range of \$1000 to \$2000/kW, as well as the incremental value of regulation control. With these value elements, VRB systems will compete favorably against alternative solutions valued at more than about \$1520/kW. As an additional indicator of NPV sensitivity with respect to the cost of energy storage, if the price of VRB-10h plants were decreased from \$20.0 million to \$19.9 million, the NPV would equal zero, i.e., costs and benefits would be equal with those for alternative solutions valued at \$1500/kW

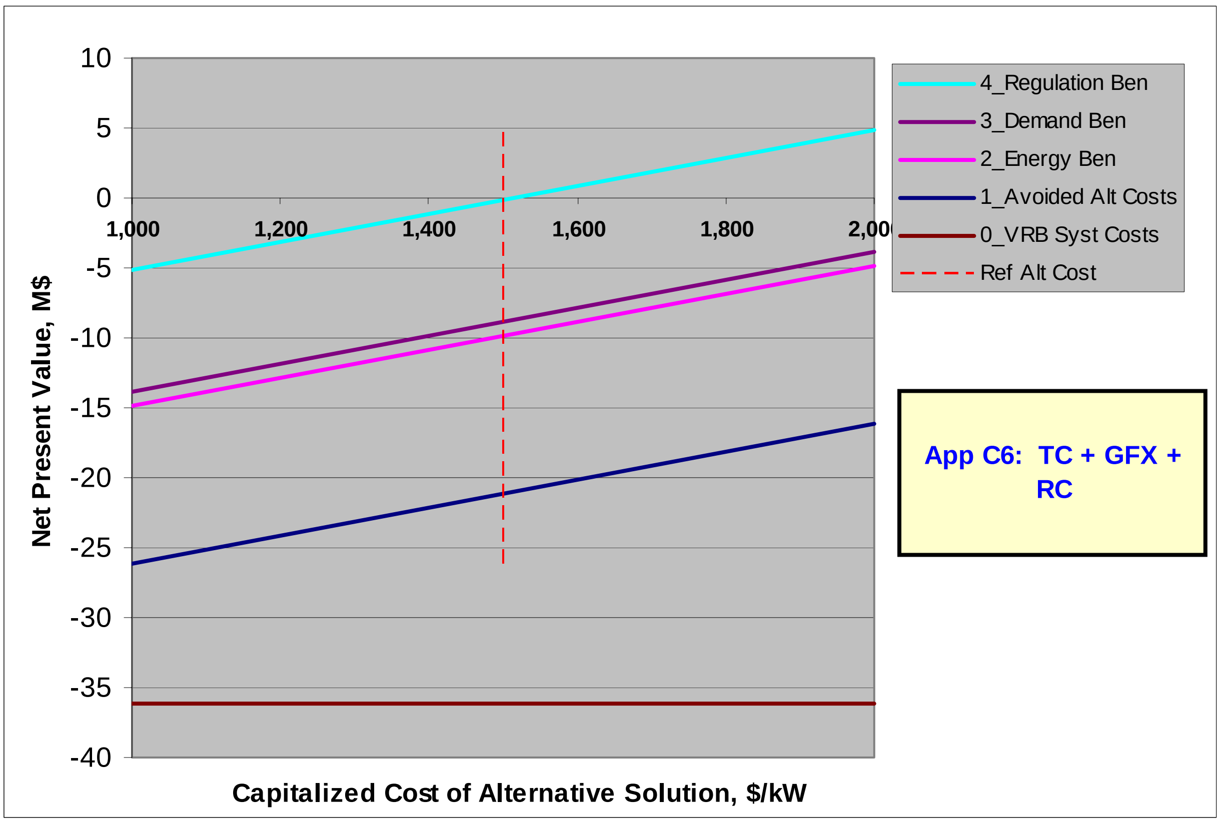

Figure 10-1
Application C6: VRB System NPV vs. Cost of Alternative Solution

- Application C7: Combined Applications K, M, D (TS + GFX + RC) – This application was evaluated on the assumption that an alternative solution capable of acquiring on-peak generation at market rates, plus avoiding GFX related upgrade costs, can be obtained for net capitalized costs of about $750/kW, including acquisition, fixed and variable O&M, and property taxes and insurance costs. As shown in Table 10-4, this application yields a negative NPV of ($2.4) million for an initial investment of about $26.9 million on this basis. As a measure of the sensitivity of NPV with respect to alternative solution costs, Figure 10-2 illustrates the change in NPV over a range of $500 to $1000/kW, as well as the incremental value of regulation control. With these value elements, VRB systems will compete favorably against alternative solutions valued at more than about $980/kW. As an additional indicator of NPV sensitivity with respect to the cost of energy storage, if the price of VRB-10h plants were decreased from $20.0 million to $18.3 million, the NPV would equal zero, i.e., costs and benefits would be equal with those for alternative solutions valued at $750/kW.

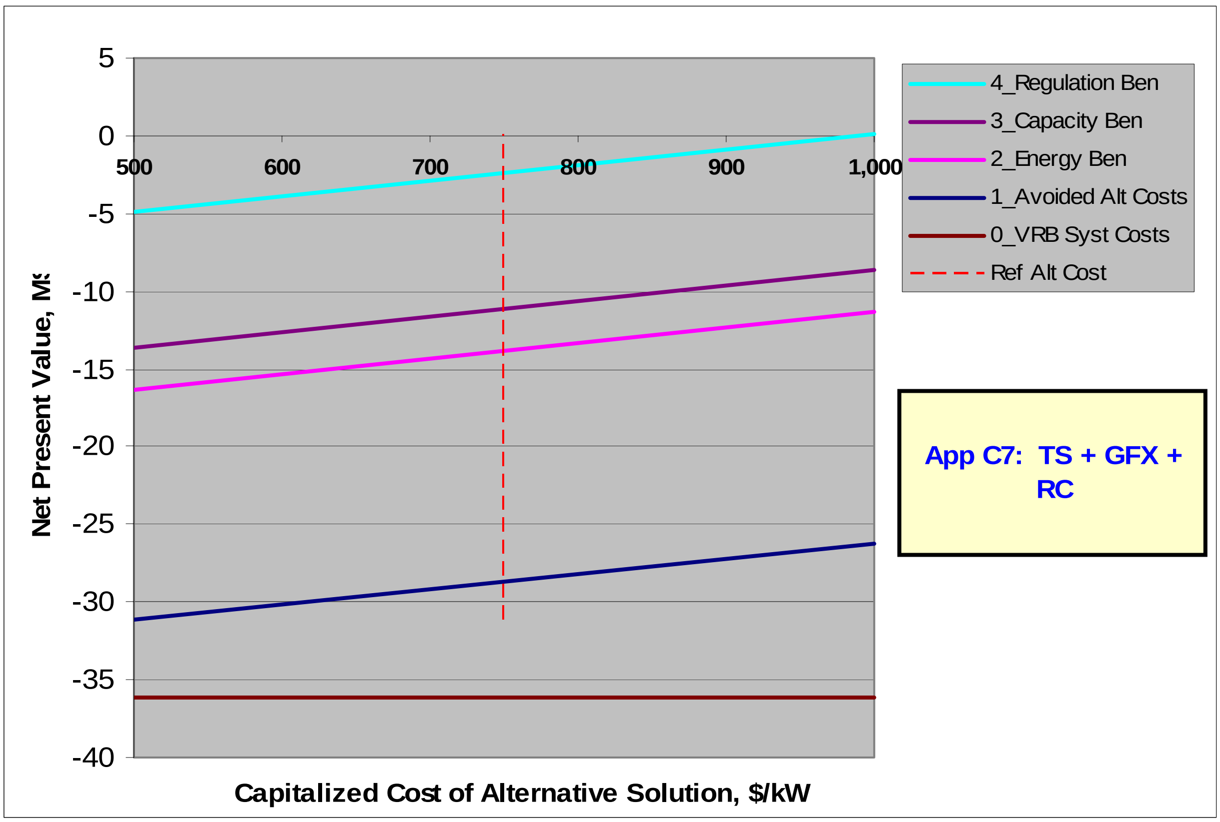

Figure 10-2
Application C7: VRB System NPV vs. Cost of Alternative Solution

- Application C8: Combined Applications L, M, D (FH + GFX + RC) – This application was evaluated on the basis of avoided risks associated with market rates and penalties for wind generation bid into the 3-hour ahead electricity market as described in Chapters 3 and 4, plus the assumption that avoided GFX related upgrade costs can be obtained for net capitalized costs of about $750/kW, including acquisition, fixed and variable O&M, and property taxes and insurance costs. As shown in Table 10-4, this application yields a NPV of $6.0 million for an initial investment of about $24.1 million on this basis. As a measure of the sensitivity of NPV with respect to alternative solution costs, Figure 10-3 illustrates the change in NPV over a range of $500 to $1000/kW, as well as the incremental value of regulation control. With these value elements, VRB systems will compete favorably against alternative solutions over this entire range. As an additional indicator of NPV sensitivity with respect to the cost of energy storage, if the price of VRB-6h plants were increased from $17.2 million to $21.5 million, the NPV would equal zero, i.e., costs and benefits would be equal with those for alternative solutions valued at $750/kW.

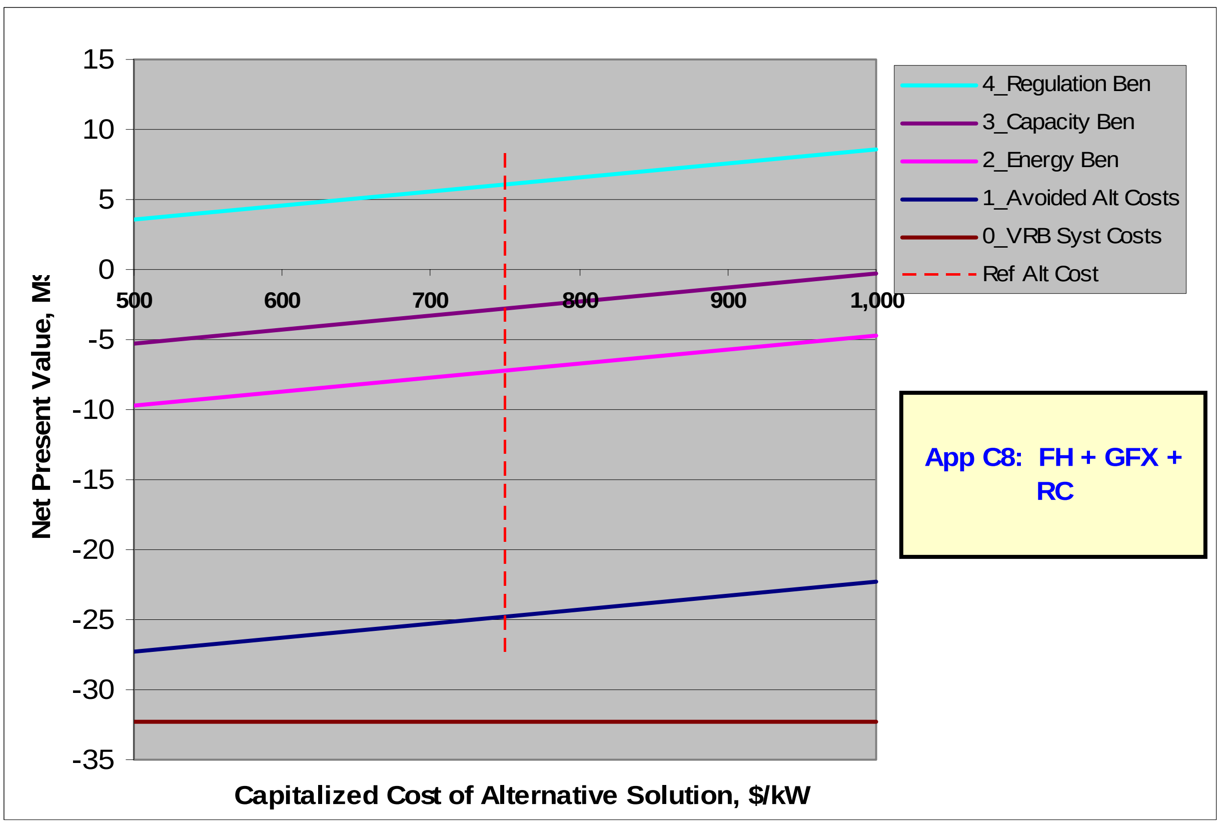

Figure 10-3
Application C8: VRB System NPV vs. Cost of Alternative Solution

- Application C9: Combined Applications N, M, K (FS + GFX + TS) – This application was evaluated on the assumption that an alternative solution capable of suppressing 2 MW fluctuations from 12 MW wind farm, plus avoided GFX related upgrade costs, can be obtained for net capitalized costs of about $1500/kW, including acquisition, fixed and variable O&M, and property taxes and insurance costs. As shown in Table 10-4, this application yields a negative NPV of ($5.5) million for an initial investment of about $25.5 million on this basis. As a measure of the sensitivity of NPV with respect to alternative solution costs, Figure 10-4 illustrates the change in NPV over a range of $1000 to $2000/kW, as well as the incremental value of time-shifting wind generation at market rates. With these value elements, VRB systems will not compete favorably within this range. (Alternative solutions with net capitalized costs in excess of about $2050/kW are required for VRB to be competitive.) As an additional indicator of NPV sensitivity with respect to the cost of energy storage, if the price of VRB-9h plants were decreased from $18.6 million to $14.6 million, the NPV would equal zero, i.e., costs and benefits would be equal with those for alternative solutions valued at $1500/kW.

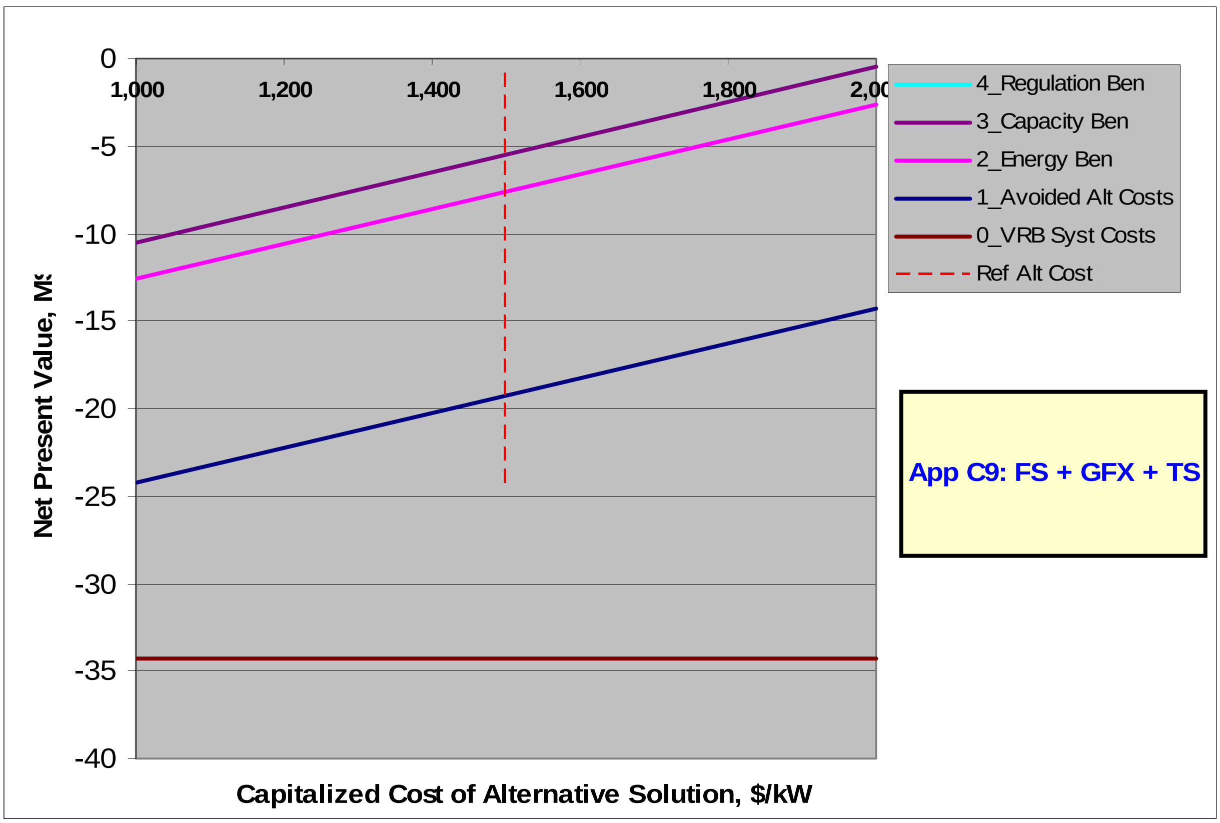

Figure 10-4
Application C9: VRB System NPV vs. Cost of Alternative Solution

Interpreting Results from Benefit-Cost Analyses

The cost and performance of the VRB battery system is marginally competitive for the combined function applications C7 and C9. However, it is progresses from competitive to attractive over the range of value parameters for the combined function applications of C6 and C8

The reader is reminded that the foregoing analyses are intended as a guide to the initial consideration of energy storage options, and that these analyses are based on representative electric rates and costs for alternative solutions as described in Chapter 4. The assumptions used herein should be reviewed in light of project specific applications, alternative solutions, electric rates and financial parameters.

References

1. Communications with Mark Kuntz, VRB Power Systems, Inc., November 2004.
2. Communications with Malcolm Jacques, Reliable Power, Inc., November 2004
3. NEDO Press Release, September 7, 2000.
4. Communications with Andrew Hickman, HydroTasmania, November 2004.
5. J-Power Press Release, September 3, 2003.
6. Communications with Rick Abe, J-Power, Summer/Fall 2004.
7. Communications with Mindi Farber-DeAnda, SAIC, November 2004.

11
POLYSULFIDE - BROMIDE BATTERIES

Update Overview

During the past year, the Polysulfide-Bromide Battery (PSB) under the brand name Regenesys was withdrawn from the market by its owner, RWE npower PLC, a subsidiary of the German based parent company RWE AG. Apparently, the remaining technical development and financial investment was incompatible with RWE's near-term priorities. The Little Barford and TVA projects have been mothballed while the owners evaluate their options for a retrofit conversion and/or decommissioning.

In September 2004, VRB Power acquired an exclusive global license from RWE for all the intellectual property and related remaining physical assets of the Regenesys technology. Because there are similarities between the two flow battery systems, VRB Power is expecting to incorporate manufacturing techniques adapted from the PSB system into their own manufacturing. Concurrently, VRB Power engaged the services of the Electrosynthesis Company Inc, who had been the in-house research arm of Regenesys based in the Buffalo, NY area, to continue the development of the Regenesys technology as well as enhancements to the VRB technology. VRB Power predicts re-introducing the PSB technology within the next few years. VRB Power would then be able to offer battery systems in a range of power and energy ratings appropriate to both flow battery technologies. For now, the PSB system is not addressed for the wind power applications of this Supplement.

12
SUPERCONDUCTING MAGNETIC ENERGY STORAGE

Update Overview

During the past year, there have been no further deployments of the Superconducting Magnetic Energy Storage (SMES) system. Instead the focus of American Superconductor, the only current vendor with a SMES offering, is on a superconducting based DVAR system for transmission level voltage control that can incorporate a SMES system as an energy storage option.

Wind Power Applicability

Further, since the shortest duration wind power application is 10 full-power seconds, the SMES option is not a practical consideration within this Supplement. However, the DVAR is utilized with wind generation to avoid voltage fluctuations into the grid and assist in low voltage ride-through applications.

13
FLYWHEEL ENERGY STORAGE

Update Overview

There have been several significant developments in the flywheel area since the publication of the Handbook in 2003. In June 2004, Urenco chose to exit the flywheel market, citing the lack of market traction in the power quality area. In the process, Urenco withdrew from a recently awarded project from the California Energy Commission to use flywheels to stabilize a transit system (similar to the Far Rockaway project described in the flywheel chapter in the Handbook). Urenco also removed all installed Urenco flywheels to eliminate product support and liability issues. Further, Urenco is not licensing its flywheel technology to others.

Beacon Power has been selected by the New York State Energy Research and Development Agency (NYSERDA) to produce a demonstration version of the company's frequency regulation system (described in the original Handbook). The demonstration project will use a version of Beacon's 6 kWh_{ac} flywheel, equipped with an upgraded motor which would allow a much higher power output. The complete system, consisting of 7 flywheels, will deliver 100 kW_{ac} for 15 minutes. Beacon currently plans to install the system at an industrial site in New York, on the utility side of the meter. Beacon has also been selected by the California Energy Commission to install a similar system in California, to be located at a substation [1].

Wind Power Technology Experience

Flywheels have not been used extensively in wind applications. Where they have been used, it has been for the suppression of fluctuations related to the short-duration variability in wind. These fluctuations present a smaller problem for the "soft-handshake" adjustable speed turbines being produced in the last few years.

In August 2003, Fuji Electric, a Japanese electric equipment and system vendor, installed a 200 kW_{ac} Urenco flywheel at an 1800 kW_{ac} wind farm on Dogo Island in Japan. The wind farm is composed of three 600 kW_{ac} De-wind D4 wind turbines, stabilized by diesel engines. The use of the flywheel helped to reduce the fluctuations on the system and allowed the diesel engines to operate at higher efficiency, reducing the use of diesel fuel [2].

Powercorp, an Australian integrator of wind power and diesel generator systems, has also experimented with flywheel systems, using flywheels built by RWE Piller. Powercorp's Intelligent Power System (IPS) is a control system that uses flywheels to stabilize small grids with wind turbines and diesel systems. The flywheel is used to absorb short-duration fluctuations in the wind power output, while the diesel systems handle long-duration intermittency. The most prominent demonstration of the Powercorp system is at the Denham Wind/Diesel Project at Denham, Western Australia. Denham operated on a virtual island powered by diesel generators, before wind power generation was installed beginning in 1998. Eventually, the site had three ENERCON wind turbines, each rated for 230 kW_{ac}. These were tied with two 200 kW_{ac} flywheels installed in parallel to provide 400 kW_{ac} for up to 90 seconds. The stabilization has allowed the diesel engines to run more efficiently, leading to significant savings in diesel fuel [3].

Select Wind Applications for Flywheel Energy Storage Systems

This section presents the wind application for which flywheels are suited and describes the key features of flywheel systems when configured to meet the application requirements. Screening economic analyses have shown that flywheel systems are potentially competitive for one of the single function applications, but none of the combined function applications, which are described in detail in Chapter 3. The following list briefly summarizes all of the Chapter 3 applications, with a reiteration of the key application requirements. Those for which flywheel systems are best suited are enclosed by borders.

Single Function Applications

Application J: Transmission Curtailment (TC) – mitigation of power delivery constraint imposed by insufficient transmission capacity. Except for large CAES, reference duty cycle for analysis is derived from the reference 60 MW Texas wind farm profile constrained to 50 MW by available transmission capacity, valued at market electricity rates for the incremental wind generation and capacity delivered, plus the value of avoided T&D upgrade.

Application K: Time-Shifting (TS) – firms and shapes wind generation via the reference NREL wind profile by storing wind generation during the off-peak interval (6:00 pm to 6:00 am), supplemented by power purchased from the grid when wind generation is inadequate, and discharged during the on-peak interval (6:00 am to 6:00 pm). Valued at the market rates for the time-shifted, shaped energy and capacity; plus the value of avoided peaking generation upgrade.

Application L: Forecast Hedge (FH) – mitigates errors (shortfalls) in wind energy bid three hours prior to a one-hour delivery interval via the reference NREL wind profile. Valued at the incremental value of wind energy and capacity delivered at market rates and avoided penalties.

Application M: Grid Frequency Support (GFX) – supports grid frequency during sudden large decreases in wind generation and similar to GFS above, i.e., "prompt" spinning reserve (or load) for mitigating load-generation imbalance. Requires energy storage to discharge real power for durations up to 30 minutes. The reference duty cycle for analysis is standby for infrequent events characterized by 15 minute FPD, 1 event per day, 10 events per year. Valued at the cost of alternative solutions...

Application N: Fluctuation Suppression (FS) – stabilizes wind farm generation frequency by suppressing fluctuations (absorbing and discharging energy during short duration variations in output). Valued at the cost of alternative solutions.

Combined Function Applications (In the Order Noted)

Application C6: Combined Applications J, M, D (TC + GFX + RC)

Application C7: Combined Applications K, M, D (TS + GFX + RC)

Application C8: Combined Applications L, M, D (FH + GFX + RC)

Application C9: Combined Applications N, M, K (FS + GFX + TS)

Flywheel Energy Storage System Compliance with Application Requirements

The flywheel module performance parameters discussed in the Handbook were used to develop approximate sizes and operational parameters for systems meeting the application requirements for the selected applications described in the previous section. Key factors in sizing flywheel systems include:

- Selection of the type of flywheel: high-energy or high-power. High-power flywheels are more appropriate for applications requiring short discharge durations. High-energy flywheels are more appropriate for applications with longer discharge durations.
- Voltage: Output voltage is often programmable, since most flywheels have an AC-DC converter.
- Standby power requirements: Some flywheels have significantly larger standby losses than others. This is particularly true of the very large low-speed flywheels.
- Location: Larger flywheels are often cheaper from a capital cost standpoint, but require more space. Some flywheels require indoor space with environmental conditions. Others can be placed outdoors or even underground. Safety and environmental conditions should also be noted when siting a flywheel.

Performance aspects of flywheel energy storage systems for the selected wind application are described below and summarized in Table 13-1. The reference power for the select application is 2 MW_{ac}. In this example, representative flywheel products have been selected and sized for the application at hand. The selected product is one found to be appropriate for this particular application on the basis of technical and economic criteria. This does not mean, however, that other flywheel devices could not also perform the same function.

- Application N: Fluctuation Suppression (FS) – This application requires that the system continuously respond to 2 MW_{ac} wind output fluctuations at the rate of 90 cycles per hour over the life of the system. The reference duty cycle for FS alone is illustrated in Figure 3-6. The energy storage system is comprised of 4 Piller PowerBridge flywheels, connected to a Type I PCS at 500 V_{dc}. The system is in continuous operation and yields a net efficiency of 96.2%. The lifetime of the flywheel is estimated to be 20 years.

Table 13-1
Flywheel System Compliance with Application Requirements

Applications	Single Functions
	App N: FS - Fluctuation Suppression
Energy Storage Selection	
Type of Product	Piller PowerBridge
Number of Strings	4
Max Charge Voltage	500
Min Discharge Voltage	500
Maximum DOD, %	100%
Replacement Interval, yr	20
PCS Selection	
PCS Type (Chapter 5)	I
Duty Cycles	
Fluctuation Suppression (FS)	
Power, MW	2.0
Hours per day, hr	24
Days per year, days	365
FS Losses, MWh/yr	665
Summary System Data	
Standby Hours per Year	0
System Net Efficiency, %	96.2%
Energy Storage Standby Efficiency, %	100.0%
PCS Standby Efficiency, %	100.0%
System Footprint, MW/sqft (MW/m^2)	0.0053 (0.0573)
Energy Storage Footprint, MW/sqft (MW/m^2)	0.0167 (0.1802)

Note: System net efficiency includes losses for energy conversion and system standby expressed on an annual basis, i.e., one minus inefficiency, where inefficiency equals the ratio of annual energy losses to the product of system rated power times 8760 hours, expressed in percent.

Benefit and Cost Analyses

Flywheel Energy Storage Pricing and Integrated System Costs

The prices of flywheel energy storage products vary somewhat with the size and maturity of the system. A representative price for the Piller PowerBridge product for this application is shown here [4]. The PowerBridge is a vertical axis steel flywheel, based on mature technology.

Flywheel System	2003 and Mature Prices, K$
Piller PowerBridge	$130

The scope of supply of each of this product includes the rotor and related mechanical components, the motor/generator, and power electronics to convert the output to dc power.

The cost of integrated flywheel systems is obtained by combining the cost of the flywheel product scope of supply with the appropriate PCS and BOP costs as described in Chapter 5 of the Handbook. The PCS and BOP costs shown in Table 13-2 are based on the methodology described in Chapter 5 of the Handbook. The cost of enclosures matches the requirement of the particular flywheel system, in accordance with guidelines specified in Chapter 3 of the Handbook. The flywheel described here must be located in interior space with environmental control. The cost for this space is included at $100/sqft.

Fixed O&M costs are based on $2/kW for the PCS as required by provisions in Chapter 5 of the Handbook, plus flywheel product maintenance in accordance with the vendor. A typical Piller maintenance program consists of an annual oil change and bearing replacement at 5-year intervals. Costs assume a standard 5-year service contract costing $15,000. In addition, an allowance for annual property taxes and insurance, based on 2% of the initial total capital costs, is included in the fixed O&M costs.

Variable O&M costs for all flywheels are based on the cost of electrical losses associated with the continuous cycling duty cycle required by this application, and to cover all parasitic and intrinsic losses in the flywheel product. Flywheel systems do not contain exotic materials and do not require special disposal. In general, the scrap value of the various components will not exceed the cost of disposal.

Table 13-2
Capital and Operating Costs for Flywheel Systems

Applications	Single Functions
	App N: FS - Fluctuation Suppression
Energy Storage Capacity, MWh_{ac}	0.003
PCS Initial Cost, $/kW	345
BOP Initial Cost, $/kW	100
Energy Storage Initial Cost $/kW	316
Energy Storage Initial Cost $/kWh	230,000
Total Capital Cost, M$	1.5
O&M Cost – Fixed, $/kW-year	23.2
O&M Cost– Variable, $/kW-year	12.6

Note: The total initial cost may be calculated in two ways:
1. By mutiplying the sum of PCS, BOP and Battery initial costs expressed in $/kW by the reference power,
2. OR by mutiplying the sum of PCS and BOP expressed in $/kW by the reference power and then adding the product of Battery Initial cost expressed in $/kWh and the Battery Capacity

Lifecycle Benefit and Cost Analysis for Flywheel Systems

Further insight to the value of energy storage can be gained through lifecycle cost analyses using a net present value (NPV) methodology and comparison with alternatives. The financial parameters in Table 13-3 are used to assess this application.

Table 13-3
Financial Parameters

Dollar Value	2003
System Startup	June 2006
Project Life, years	20
Discount Rate (before tax), %	7.5
Property Taxes & Insurance, %/year	2
Fixed Charge Rate, %/year	9.81

The results of lifecycle benefit - cost analyses for this flywheel application are summarized in Table 13-4 and discussed below. The bases and methodology used in valuing energy storage applications is described in detail in Chapter 4 of the Handbook. The details of the cost benefit analysis for each application are discussed below.

Table 13-4
Summary of Benefit and Cost Analyses of Flywheel Systems

Applications	Single Functions
	App N: FS - Fluctuation Suppression
Alt Solution Value, $/kW	750
Initial Installed Cost, M$	1.52
Total Costs, M$	(2.3)
Total Benefits, M$	1.5
Benefit to Cost Ratio	0.67
NPV, M$	(0.8)
Energy Storage Module	Piller PowerBridge
Number of Modules	4
Energy Storage 2006 Price, K$/module	130
Energy Storage Price for NPV=0, K$/module	26

- Application N: Fluctuation Suppression (FS) – This application was evaluated on the assumption that an alternative system capable of suppressing fluctuations at wind farm output can be obtained for capitalized costs of about $750/kW, including acquisition, fixed and variable O&M, and property taxes and insurance costs. As shown in Table 13-4, this application yields a negative NPV of ($0.8) million for an initial investment of about $1.5 million. As a measure of the sensitivity of NPV with respect to alternative system costs, Figure 13-1 illustrates the change in NPV over a range of $500 to $1000/kW, and shows that flywheel systems will not compete against alternative solutions over this range of net capitalized costs. (Flywheel systems are competitive against alternative solutions value at more than about $1100/kW.) As an additional indicator of NPV sensitivity with respect to the cost of energy storage, if the price of flywheel system were decreased from $130 to $26 thousand per module, the NPV would equal zero, i.e., costs and benefits would be equal with those for alternative solutions valued at $750/kW.

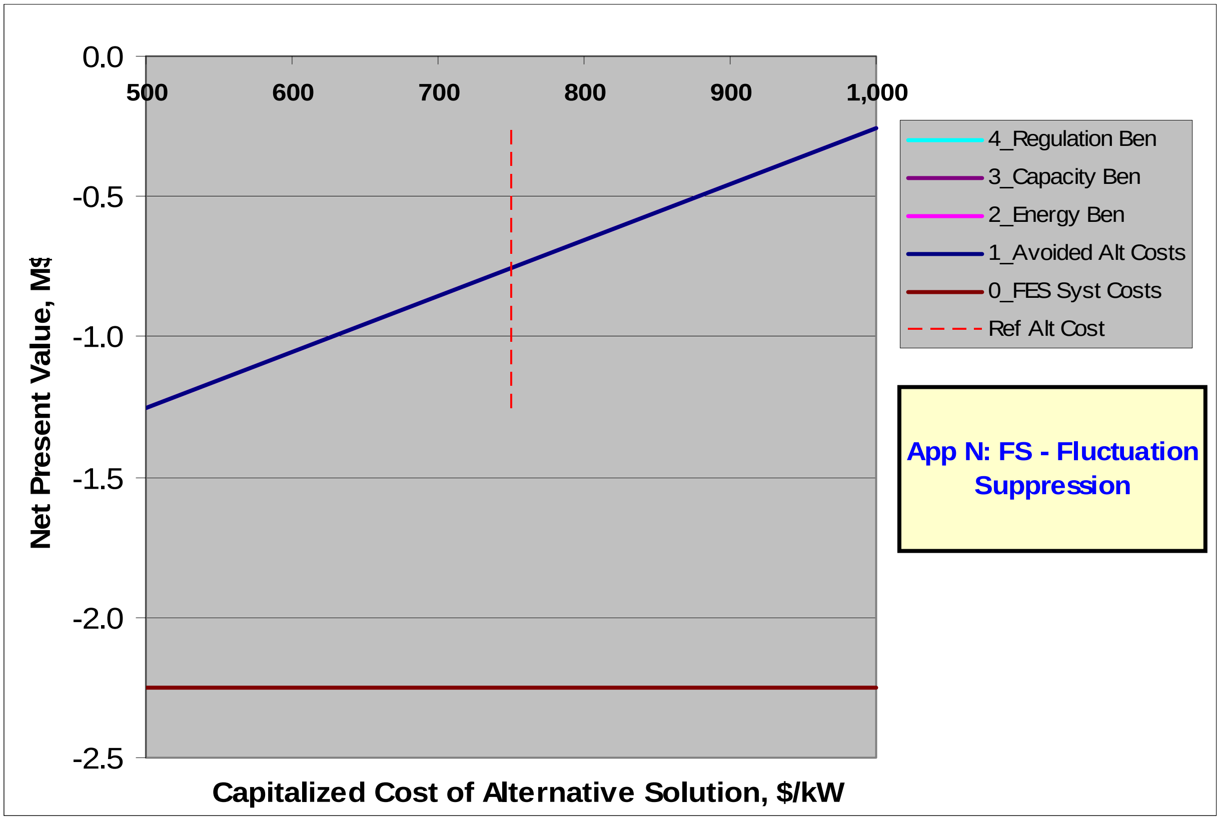

Figure 13-1
Application N: Flywheel System NPV vs Cost of Alternative System

Interpreting Results from Benefit-Cost Analyses

As noted in the footnote on page 3-5, in conducting assessments of energy storage options for this application, this duty cycle for Fluctuation Suppression was been found to be onerous for short duration energy storage media such as ultracapacitors and flywheels. This suggests that the requirement to continuously mitigate fluctuations may be overly severe and should be reconsidered in light of actual wind data in future evaluations. The results of this study should not preclude the consideration of such technologies in similar applications with less rigorous requirements.

The reader is reminded that the foregoing analyses are intended as a guide to the initial consideration of energy storage options, and that these analyses are based on representative electric rates and costs for alternative solutions as described in Chapter 4. The assumptions used herein should be reviewed in light of project specific applications, alternative solutions, electric rates and financial parameters.

References

1. Communications with Matt Lazarewicz of Beacon Power, November 2004.

2. Urenco Power Technologies, “Fuji Wind Diesel Power Case Study,” http://www.uptenergy.com/eng/applications/renewablepower/casestudy/fuji.htm

3. Powercorp website, www.pcorp.com.au

4. Communications with Kevin Collins, Piller, November 2004.

14
ELECTROCHEMICAL CAPACITORS

Update Overview

Ultracapacitor technology continues to progress, with a number of significant advances occurring in the year 2004. Most advances have been incremental advances in technology with some repercussions in products, with the following general trends:

- More ultracapacitor manufacturers are recognizing the market for integrated ultracapacitor modules composed of multiple ultracapacitor cells in series with built-in cell leveling circuitry.
- Many vendors are now focusing on reducing costs through improved manufacturing, and in new applications for existing ultracapacitor products, rather than improving product specifications.
- Greater interest from the automotive and utility industries has spurred efforts in high energy density, high cycle life ultracapacitors for application in hybrid electric vehicles, electric transit systems, and similar applications.
- Relatively high voltage ultracapacitor systems are beginning to appear, especially in transit and utility applications.
- As limits of the electrical double-layer capacitance energy storage mechanism are more understood, long-term research is beginning to head towards mechanisms using faradic reactions, including asymmetric ultracapacitors and pseudocapacitors.

Wind Power Technology Experience

Ultracapacitors have not been used for wind power applications as of yet, but have been proposed for stabilization of fluctuations in at least one instance. In July 2004, Hawaiian Electric Company (HECO) received a patent for an “electronic shock absorber,” a device which would use ultracapacitors to dampen frequency fluctuations caused by short duration fluctuations in wind. Such fluctuations have a particularly heavy impact on smaller, weaker grids, such as the electric system on the Big Island of Hawaii.

The Big Island has a peak power load of 180 MW_{ac}, and a minimum load of 80 MW_{ac}. The island has a total installed power generation capacity of about 255 MW_{ac}, including an installed wind capacity of about 9 MW_{ac}. While the total installed wind power is small by mainland standards, it is large enough in relation to the system load that fluctuations in the wind power generation lead to serious impacts on grid frequency, particularly during periods of minimum load.

To suppress fluctuations from the wind farm, HECO has proposed a system comprising an ultracapacitor energy storage system, a control system, and an electronic compensation module between the wind farm and power transmission line. The system is designed to level the output of wind turbines, by providing power from the ultracapacitor system as the wind flags, and recharging the ultracapacitor system when the wind gusts. A prototype of the design is now being produced by S&C Electric Company's Power Quality Products Division. The 500 kW_{ac} prototype is expected to be tested in 2005 [1].

In parallel to the HECO process, Hawaiian Electric Light Company (HELCO), a subsidiary of HECO, has worked with SENTECH, Inc. under a grant from the U.S. Department of Energy to examine energy storage solutions for transmission problems on the Big Island. The installation of significant amounts of non-dispatchable renewable power generation – including wind power – on the island, as well as the increase in development and growth on the western side of the island, away from the generation centers on the eastern side, has made it necessary to upgrade the island's transmission network. While part of this will be accomplished through traditional transmission upgrades, energy storage is also being examined as an option.

In this application, it is expected that an energy storage plant would have to be significantly sized, in terms of both power and energy. HELCO and SENTECH have identified the need for one 20 MW_{ac}, 30 MWh_{ac} system or two 10 MW_{ac}, 15 MWh_{ac} energy storage systems at different locations. While there are several long-duration energy storage technologies viable for this application, it seems unlikely that ultracapacitors will fall among them, at least at the current level of development [2].

Wind Power Applicability

Commercially available ultracapacitor technology was assessed for potential use in Application N, Fluctuation Suppression, described in Chapter 3. However, at this time, no products were identified that meet the cost and performance criteria for inclusion in this Supplement. It should be noted that the continuous, 90 cycles per hour, duty cycle required by Applications N is particularly onerous for short duration energy storage media such as ultracapacitors and flywheels. The results of this study should not preclude their consideration in similar applications with less rigorous demands.

Select Wind Applications for Flywheel Energy Storage Systems

Ultracapacitor energy storage was assessed for Application N, Fluctuation Suppression, but the cycle life of known commercial products was found to prevent meeting cost and performance criteria for inclusion in this Supplement.

Interpreting Results from Benefit-Cost Analyses

As noted in the footnote on page 3-5, in conducting assessments of energy storage options for this application, this duty cycle for Fluctuation Suppression was been found to be onerous for short duration energy storage media such as ultracapacitors and flywheels. This suggests that the requirement to continuously mitigate fluctuations may be overly severe and should be reconsidered in light of actual wind data in future evaluations. The results of this study should not preclude the consideration of such technologies in similar applications with less rigorous requirements.

References

1. HECO Press Release, July 19, 2004.

2. HELCO, Inc. and Sentech, "HELCO Operational Issues – Bulk Energy Storage," Draft in November 2004.

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15
COMPRESSED AIR ENERGY STORAGE

Update Overview

During the past year, Compressed Air Energy Storage (CAES) project development has advanced with emphasis on wind power applications, as described below.

Experience with Wind Power Applications

The effectiveness of CAES systems in bulk storage has made it highly attractive for large wind power applications, but no CAES systems have yet been built solely for wind. Two studies in the U.S. are possible precursors to CAES systems; the first has been done for a large wind area in West Texas, and the other for a section of Iowa.

CAES in West Texas

The rapid development of wind generation assets in West Texas in the early 2000s quickly outpaced the growth of available transmission. Transmission congestion resulted in severe curtailment of generated wind power. Further, the system operator, Electric Reliability Council of Texas (ERCOT), was obligated to pay wind developers for lost energy production. The details of the West Texas case are discussed in Reference [1].

ERCOT moved rapidly to develop a plan to upgrade the existing transmission assets, supported by wind developers who sought to build more wind generation in the area. In the meantime, the Texas State Energy Conservation Office (SECO) commissioned a study to examine whether energy storage could be used to defer or replace construction of new transmission assets. This study was conducted by Lower Colorado River Authority (LCRA) in association with Ridge Energy Storage & Grid Services, RnR Engineering, and Walter J. Reid Consulting [1]. The LCRA study focused on the technical ability of energy storage to reduce curtailments and provide reactive power support, leaving other transmission issues such as dynamic stability as well as market and regulatory issues to later efforts.

The study began by identifying the most likely energy storage technologies for integration with wind energy in West Texas. It was found that curtailment reduction at a useful scale would require the storage and delivery of large power and energy ratings. Two technologies have demonstrated proven capability at this scale: pumped hydroelectric, and CAES. The geography of West Texas is not favorable to the construction of pumped hydroelectric systems, but there is significant potential for CAES installations. For this reason, CAES was chosen as the most likely candidate technology for an energy storage installation in this location.

The study examined a proposed CAES plant with 400 MW_{ac} compression power and 270 MW_{ac} generation capacity with an energy storage capacity of 10,000 MWh_{ac}. The fixed cost of the plant was estimated at between $215 and $225 million. This estimate included the engineering, procurement, and construction costs for cavern development and the CAES plant, as well as development costs and fees, startup costs, and working capital. This capital cost translates into annual carrying cost of about $30 million/year, covering interest and principal on debt as well as return to equity investors under an appropriate financing structure. Also included are recurring fixed expenses such as upkeep, property taxes, insurance, business management and utilities. Fuel costs were estimated at $5/mmBtu. Variable O&M cost was estimated to range between $3 and $4 per MWh of CAES generation. In addition, $0.50 per MWh stored is included for qualified scheduling entity (QSE) fees. The analysis assumed that the cost of compression would be zero, since the wind power would have otherwise been curtailed.

The initial study found that a CAES plant would provide wind energy curtailment reduction of over 600,000 MWh. The ability of energy storage to remove curtailment was limited by the storage capacity, however; with the assumed wind-generation profiles, the energy storage capacity often fills up, so that the operator has no choice but to curtail generation. Since the CAES plant does not completely eliminate curtailment, it does not entirely substitute for transmission upgrades. It should be noted that this initial study was conducted only with regards to the transmission benefits of energy storage, without examination of other services such as firming and shaping.

A later study by Ridge Energy Storage completed the cost/benefit analysis, showing how the value of curtailment reduction compared to the cost of a CAES plant [2]. The Ridge Energy model identified several other value streams for a CAES plant, as well as making assumptions about the growth of wind generation and the schedule for transmission upgrades in the West Texas area. Based on these assumptions, Ridge Energy developed a calculation of the time-phased benefits arising from the CAES systems. Ridge Energy is now working with more detailed wind data from the West Texas area to demonstrate the fidelity of their model. Results from the further study are forthcoming.

CAES in Iowa

The Iowa Stored Energy Plant (ISEP) committee was formed in 2001 by members of the Iowa Association of Municipal Utilities (IAMU), a nonprofit organization of over 500 water, electric, and gas utilities providing municipal services across Iowa. ISEP grew out of the Iowa Energy Project, a joint action conducted by municipal utilities in Iowa and Minnesota to investigate renewable options and energy efficiency as solutions for continued load growth in their service territories.

In 2002, the ISEP committee commissioned a study of the St. Peter aquifer near Ft. Dodge in north central Iowa as the possible site of a CAES plant [3]. The aquifer had formerly been used for natural gas storage, and lay in an area with good wind resources and access to the transmission grid. The system as proposed would consist of 25 to 200 MW_{ac} of wind generation paired with a 100 to 200 MW_{ac} CAES power plant. The CAES plant could be charged from either wind or from off-peak power from the grid

As of late 2004, the geologic studies have been completed for the Iowa site, and the ISEP committee had made a proposal to the owner of the proposed site [4]. An economic analysis conducted by Black and Veatch was slated for completion and publication by the end of November 2004. If plans for the ISEP plant proceed, the plant is scheduled to begin operation by 2009.

Wind Generation Energy Storage System Applications

General CAES Applications and Costs

The capital cost of a CAES plant is a function of the storage medium, the plant capacity (power), and the energy stored in the storage medium. Table 15-1 gives the values for the capital cost components of reference CAES plants as a function of some of the plant variables. As indicated below, updates have been applied based on current estimates being used in the marketplace [1, 2, 5]. These data, along with representative operating costs, were used in the assessment of potential CAES applications described in the following sections.

Table 15-1
Representative CAES Plant Capital Costs [See Note 1]

Storage Media for CAES Plant	Size (MW_{ac})	Cost for Power-Related Plant Components ($/kW)	Cost for Balance of Power Plant ($/kW)	Cost for the Energy Storage Components ($/kWh)	"Typical" Hours of Storage for a Plant	Total Cost ($/kW)
Salt	300	~~270~~ 300	~~170~~ 210	~~1~~ 1.75 (Note 2)	~~10~~ 40	~~450~~ 580
Surface Piping (Note 3)	10	~~270~~ 300	~~160~~ 200	40	~~3 & 10~~ 5, 10 & 12	~~550 & 830~~ 700, 900 & 980

Notes:
1. Values with strikethrough were used in the Handbook, and values with underline are used in this Supplement as representative of a leading vendor's current experience.
2. The reference energy storage capacity for large CAES technologies is 10 hours. A representative price for CAES systems over the range of 8 to 40 hours storage can be obtained by applying increments/decrements at the rate of $1.75/kWh.
3. Costs for CAES plants using surface piping are based on the assumption that codes and standards used within the gas piping industry are applicable. This assumption and the associated cost projections are subject to confirmation.

Select Applications for CAES Systems

This section presents the applications for which CAES systems are suited and describes the key features of CAES systems configured to meet the requirements of the selected applications. Screening economic analyses have shown that both small and large CAES systems are potentially competitive for three of the single function applications and all four of the combined function applications. Applications are described in detail in Chapter 3. The following list briefly summarizes and reiterates key requirements for all applications. Those for which CAES is best suited are enclosed by borders. This list identifies the applications for which both small (e.g., 10 MW_{ac} with 5, 10 and 12 hour pipeline piping storage) and large (e.g., 300 MW_{ac} with 10 and 40-hour geologic salt dome storage) CAES systems are evaluated.

Single Function Applications

Application J: Transmission Curtailment (TC) – mitigation of power delivery constraint imposed by insufficient transmission capacity. Except for large CAES, reference duty cycle for analysis is derived from the reference 60 MW Texas wind farm profile constrained to 50 MW by available transmission capacity, valued at market electricity rates for the incremental wind generation and capacity delivered, plus the value of avoided T&D upgrade.

Application K: Time-Shifting (TS) – firms and shapes wind generation via the reference NREL wind profile by storing wind generation during the off-peak interval (6:00 pm to 6:00 am), supplemented by power purchased from the grid when wind generation is inadequate, and discharged during the on-peak interval (6:00 am to 6:00 pm). Valued at the market rates for the time-shifted, shaped energy and capacity; plus the value of avoided peaking generation upgrade.

Application L: Forecast Hedge (FH) – mitigates errors (shortfalls) in wind energy bid three hours prior to a one-hour delivery interval via the reference NREL wind profile. Valued at the incremental value of wind energy and capacity delivered at market rates and avoided penalties.

All for small CAES at 10 MW_{ac} and large CAES at 300 MW_{ac}

Application M: Grid Frequency Support (GFX) – supports grid frequency during sudden large decreases in wind generation and similar to GFS above, i.e., "prompt" spinning reserve (or load) for mitigating load-generation imbalance. Requires energy storage to discharge real power for durations up to 30 minutes. The reference duty cycle for analysis is standby for infrequent events characterized by 15 minute FPD, 1 event per day, 10 events per year. Valued at the cost of alternative solutions...

Application N: Fluctuation Suppression (FS) – stabilizes wind farm generation frequency by suppressing fluctuations (absorbing and discharging energy during short duration variations in output). Valued at the cost of alternative solutions.

Combined Function Applications (In the Order Noted)

Application C6: Combined Applications J, D (TC + RC)

Application C7: Combined Applications K, D (TS + RC)

Application C8: Combined Applications L, D (FH + RC)

All for small CAES at 10 MW_{ac} and large CAES at 300 MW_{ac}

Application C9: Combined Applications N, K (FS + TS)

For small CAES at 10 MW_{ac}

Assessment of Small (10 MW_{ac}) CAES Systems

Small (10 MW_{ac}) CAES System Compliance with Application Requirements

The CAES system performance parameters discussed above were used to develop approximate sizes and operational parameters for systems meeting the application requirements for the selected CAES applications described in the previous section. Performance aspects of CAES systems for the selected applications are described below and summarized in Table 15-2. The reference power for applications in this section is 10 MW_{ac}.

- Application J: Transmission Curtailment (TC) – This application requires that the system store energy when wind generation exceeds transmission capacity in accordance with Texas wind profile. Response within minutes is required. The CAES system for this application optimized for 12 hours storage for a duty cycle equivalent of 125 days per year.
- Application K: Time-Shifting (TS) – This application requires that the system store off-peak wind and purchased energy for discharge during the on-peak interval in accordance with NREL wind profile. Response within minutes is required. The CAES system for this application optimized for 10 hours storage for a duty cycle equivalent of 350 days per year.
- Application L: Forecast Hedge (FH) – This application requires that the system supply stored energy to supplement wind generation upon demand in accordance with NREL wind profile. Prompt system response is required. The CAES system for this application optimized for 5 hours storage for a duty cycle equivalent of 240 days per year.

Table 15-2
Small (10 MW_{ac}) CAES System Compliance with Application Requirements

	Single Function			Combined Function			
Applications	**App J: TC - Avoided Xmsn Curtailment, TX Wind**	**App K: TS - Time Shift, NREL Wind**	**App L: FH - Forecast Hedge, NREL Wind**	**App C6: TC + RC**	**App C7: TS + RC**	**App C8: FH + RC**	**App C9: FS + TS**
Storage Designation	10MW-12h	10MW-10h	10MW-5h	10MW-12h	10MW-10h	10MW-5h	10MW-10h
Power Plant							
Combustion Turbine				CT			
Duty Cycles							
Grid Support or Power Quality (GS or PQ)							
Power, MW							10
Event Duration, Hr							0.001
Generation Shifting (TC, TS or FH)							
Power, MW	10	10	10	10	10	10	8
Hours per day, hr	12	10	5	12	10	5	10
Days per year, days	125	350	240	125	350	240	350
Generation Shift Energy, MWh/yr	18,708	43,800	14,981	18,708	43,800	14,981	35,040
Regulation Control (RC)							
Power, MW				10	10	10	
Hours per day, hr				20	20	20	
Days per year, days				350	350	350	
RC, MW-Hours/yr				70,000	70,000	70,000	

- Application C6: Combined Applications J, D (TC + RC) – This application requires that the system store energy when wind generation exceeds transmission capacity, plus provide regulation control. Response within minutes is required. The CAES system for this application optimized for 12 hours storage for a duty cycle equivalent of 125 days per year for TC functions, and is assumed to provide RC for 20 hours per day, 350 days per year.
- Application C7: Combined Applications K, D (TS + RC) – This application requires that the system store wind generated or purchased energy during the off-peak period for discharge during the on-peak period, plus provide regulation control. Response within minutes is required. The CAES system for this application optimized for 10 hours storage for a duty cycle equivalent of 350 days per year for TC functions, and is assumed to provide RC for 20 hours per day, 350 days per year.
- Application C8: Combined Applications L, D (FH + RC) – This application requires that the system store wind generated in excess of the bid amount, and/or purchased energy during the off-peak period, for use in mitigating shortfalls in the 3-hour ahead bid forecast market , plus provide regulation control. Prompt system response is required. The CAES system for this application optimized for 5 hours storage for a duty cycle equivalent of 240 days per year, and is assumed to provide RC for 20 hours per day, 350 days per year
- Application C9: Combined Applications N, K (FS + TS) – This application requires that the system serve as a varying load at night to absorb the power fluctuations and a varying source during the day to compensate the fluctuations, such that fluctuations are suppressed for grid access. In addition, the system stores wind generated or purchased energy during the off-peak period for discharge during the on-peak period. The CAES system for this application optimized for 10 hours storage for a duty cycle equivalent of 350 days per year.

Benefit and Cost Analyses for Small (10 MW_{ac}) CAES

CAES Pricing and Integrated System Costs

The installed costs for 10 MW_{ac} CAES with 5, 10 and 12 hours storage are $7.0, 9.0 and 9.8 million, respectively. These units use piping designed to natural gas transmission and distribution pipeline standards to store compressed air. Capital and operating costs are summarized in Table 15-3, where initial costs include acquisition, space and installation costs; fixed O&M costs include projected annual costs for parts and labor, plus annual property taxes and insurance (based on 2% of the initial total capital costs); and variable O&M costs include costs for fuel and other variable consumables.

Table 15-3
Capital and Operating Costs for Small (10 MW_{ac}) CAES Systems

Applications	App J: TC - Avoided Xmsn Curtailment, TX Wind	App K: TS - Time Shift, NREL Wind	App L: FH - Forecast Hedge, NREL Wind	App C6: TC + RC	App C7: TS + RC	App C8: FH + RC	App C9: FS + TS
	Single Function			Combined Functions			
CAES Storage Capacity, MWh_{ac}	120	100	50	120	100	100	80
CT Initial Cost, $/kW	300	300	300	300	300	300	300
BOP Initial Cost, $/kW	200	200	200	200	200	200	200
CAES Storage Initial Cost, $/kW	480	400	200	480	400	200	400
CAES Storage Cost, $/kWh	40	40	40	40	40	20	50
Total Capital Cost, M$	9.8	9.0	7.0	9.8	9.0	7.0	9.0
O&M Cost – Fixed, $/kW-year	32.6	31.0	27.0	32.6	31.0	27.0	31.0
O&M Cost– Variable, $/kW-year	9.4	21.9	7.5	26.9	39.4	25.0	17.5

Note: The total initial cost may be calculated in two ways:
1. By mutiplying the sum of PCS, BOP and Battery initial costs expressed in $/kW by the reference power,
2. OR by mutiplying the sum of PCS and BOP expressed in $/kW by the reference power and then adding the product of Battery Initial cost expressed in $/kWh and the Battery Capacity

As a rule of thumb for a "generic" CAES plant, the operating cost per kWh delivered during power generation mode is the factor "K" times that of the incremental cost per kWh of off-peak power purchased during the compression mode, plus the cost of the fuel (in $/MMBtu) times the plant heat rate, "H_R". For the purposes of evaluating 10 MW_{ac} CAES configuration, K and H_R have been defined as 0.8 and 4500 Btu/kWh [1, 5], respectively, i.e.:

Cost of electricity generated ($/kWh) = (0.80) (Incremental cost of electricity purchased, $/kWh) + (Cost of fuel purchased, $/MMBtu) (4,500 Btu/kWh) / (1,000,000 Btu/MMBtu)

The factor, K, includes the ratio of generated electricity to purchased electricity and the energy lost to pipe friction, air leakage, pressure regulation, and compressor/expander component efficiencies. The heat rate, H_R, is typical for an expander-generator set operating without the compressor during the generation mode.

For 10 MW_{ac} CAES, fixed O&M costs are based on $13/kW-year [5], plus property taxes and insurance; and variable O&M costs are based on $0.005/kWh, plus fuel costs calculated for a heat rate of 4,500 Btu/kWh and natural gas fuel priced at $5/MMBtu.

Lifecycle Benefit and Cost Analysis for Small (10 MW_{ac}) CAES Systems

Further insight to the value of energy storage can be gained through lifecycle cost analyses using a net present value (NPV) methodology and comparison with alternatives. For the convenience of the reader, the financial parameters set forth in Chapter 5 of the Handbook and used in the analyses are summarized in Table 15-4.

Table 15-4
Financial Parameters

Dollar Value	2003
System Startup	June 2006
Project Life, years	20
Discount Rate (before tax), %	7.5
Property Taxes & Insurance, %/year	2
Fixed Charge Rate, %/year	9.81

The results of lifecycle cost benefit analyses of select CAES applications are summarized in Table 15-5 and discussed below. The bases and methodology used in valuing energy storage applications are described in detail in Chapter 4. The details of the cost benefit analysis for each application are discussed below.

Table 15-5
Summary of Benefit and Cost Analyses of Small (10 MW_{ac}) CAES Systems

	Single Functions			Combined Functions			
Applications	App J: TC - Avoided Xmsn Curtailment, TX Wind	App K: TS - Time Shift, NREL Wind	App L: FH - Forecast Hedge, NREL Wind	App C6: TC + RC	App C7: TS + RC	App C8: FH + RC	App C9: FS + TS
Alt Solution Value, $/kW	750	0	0	750	0	0	750
Storage Designation	10MW-12h	10MW-10h	10MW-5h	10MW-12h	10MW-10h	10MW-5h	10MW-10h
Initial Cost, M$	9.8	9.0	7.0	9.8	9.0	7.0	9.0
Total Costs, M$	(14.1)	(14.4)	(10.5)	(15.9)	(16.2)	(12.3)	(13.9)
Total Benefits, M$	12.6	28.0	16.2	24.1	39.4	27.6	29.7
Benefit to Cost Ratio	0.9	1.9	1.5	1.5	2.4	2.2	2.1
NPV, M$	(1.4)	13.6	5.7	8.2	23.2	15.3	15.8

- Application J: Transmission Curtailment (TC) – This application was evaluated on the assumption that transmission upgrade to avoid curtailment can be obtained for net capitalized costs of about $750/kW, including acquisition, fixed and variable O&M, and property taxes and insurance costs, but excluding incremental revenue from avoided curtailment. As described in Chapter 4, energy storage value is derived from energy storage costs plus the difference between the value of revenue from the transmission upgrade solution and the energy storage solution. As shown in Table 15-5, this application yields a negative NPV of ($1.4) million for an initial investment of about $9.8 million, corresponding to a total benefit to cost ratio of 0.9. As a measure of the sensitivity of NPV with respect to transmission upgrade costs, Figure 15-1 illustrates the change in NPV over a range of $500 to $1000/kW and shows that small CAES systems with 12 hours storage are competitive with alternatives valued at more than about $890/kW.

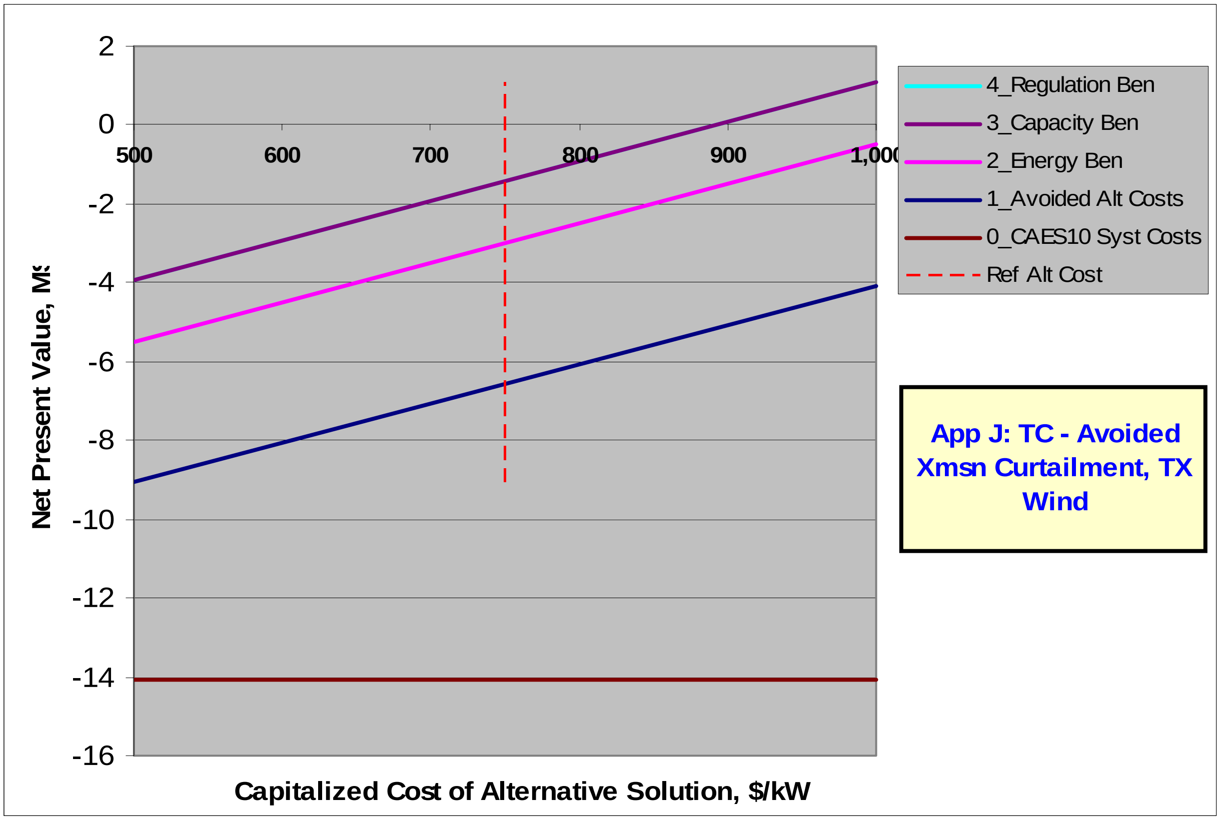

Figure 15-1
Application J: Small (10 MW_{ac}, 12 Hr Storage) CAES System NPV vs Cost of Alternative Solution

- Application K: Time-Shifting (TS) – This application was evaluated on the assumption that an alternative solution capable of acquiring on-peak generation can be obtained at market rates. As shown in Table 15-5, this application yields an NPV of $13.6 million for an initial investment of about $9.0 million, , corresponding to a total benefit to cost ratio of 1.9.
- Application L: Forecast Hedge (FH) – This application was evaluated on the basis of avoided risks associated with market rates and penalties for wind generation bid into the 3-hour ahead electricity market as described in Chapters 3 and 4. As shown in Table 15-5, this application yields an NPV of $5.7 million for an initial investment of about $7.0 million, corresponding to a total benefit to cost ratio of 1.5.
- Application C6: Combined Applications J, D (TC + RC) – This application was evaluated on the assumption that an alternative solution capable of mitigating TC events can be obtained for net capitalized costs of about $750/kW, including acquisition, fixed and variable O&M, and property taxes and insurance costs, plus the value of regulation control at market rates. As shown in Table 15-5, this application yields an NPV of $8.2 million for an initial investment of about $9.8 million, corresponding to a total benefit to cost ratio of 1.5. As a measure of the sensitivity of NPV with respect to alternative solution costs, Figure 15-2 illustrates the change in NPV over a range of $500 to $1000/kW, as well as the incremental value of regulation control, and shows that CAES systems will compete favorably over the entire range.

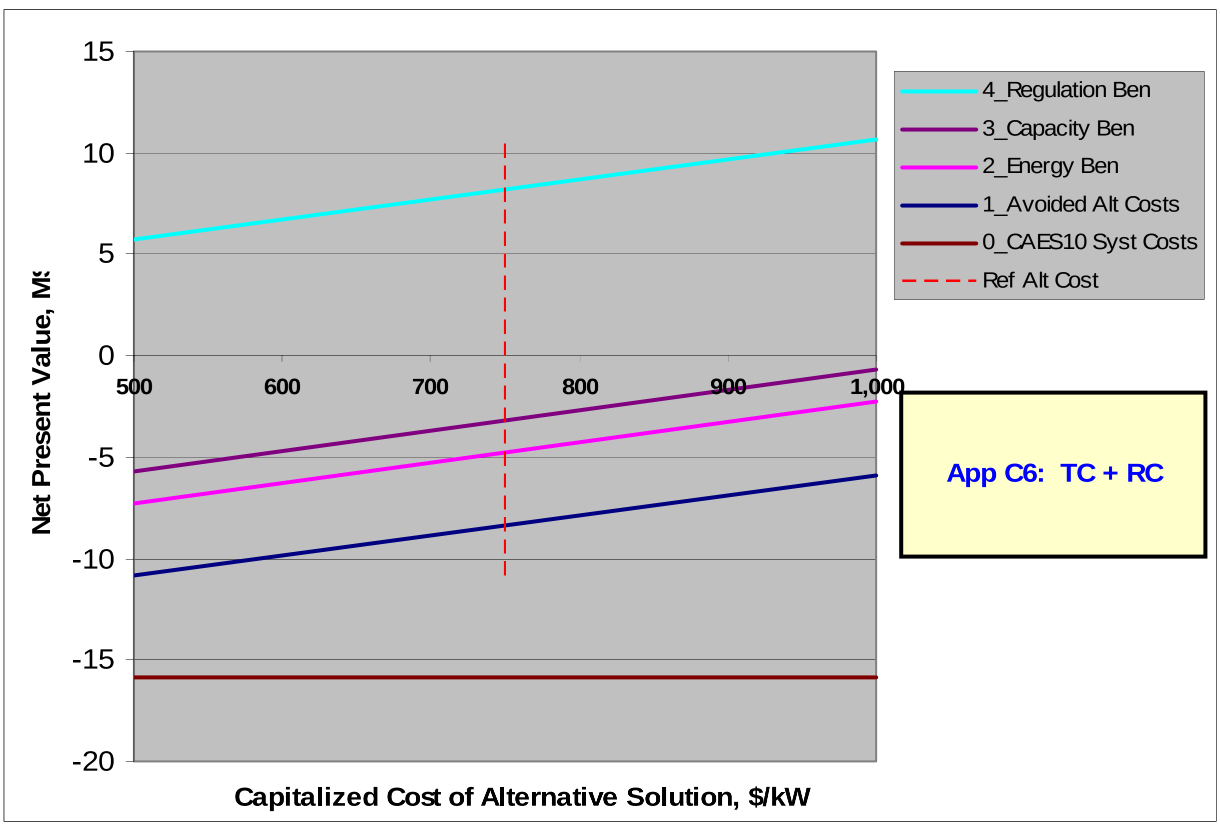

Figure 15-2
Application C6: Small (10 MW_{ac}, 12 Hr Storage) CAES System NPV vs Cost of Alternative Solution

- Application C7: Combined Applications K, D (TS + RC) – This application was evaluated on the assumption that an alternative solution capable of acquiring on-peak generation at market rates can be obtained, plus the value of regulation control at market rates.. As shown in Table 15-5, this application yields an NPV of $23.2 million for an initial investment of about $9.0 million, corresponding to a total benefit to cost ratio of 2.2.
- Application C8: Combined Applications L, D (FH + RC) – This application was evaluated on the basis of avoided risks associated with market rates and penalties for wind generation bid into the 3-hour ahead electricity market as described in Chapters 3 and 4 plus the value of regulation control at market rates. As shown in Table 15-5, this application yields an NPV of $15.3 million for an initial investment of about $7.0 million, corresponding to a total benefit to cost ratio of 2.2.
- Application C9: Combined Applications N, K (FS + TS) – This application was evaluated on the assumption that an alternative solution capable of suppressing 2 MW fluctuations from 12 MW wind farm can be obtained for net capitalized costs of about $750/kW, including acquisition, fixed and variable O&M, and property taxes and insurance costs. As shown in Table 15-5, this application yields an NPV of $15.8 million for an initial investment of about $9.0 million, corresponding to a benefit to cost ratio of 2.1. As a measure of the sensitivity of NPV with respect to alternative solution costs, Figure 15-3 illustrates the change in NPV over a range of $500 to $1000/kW, as well as the incremental value of regulation control, and shows that CAES systems will compete favorably over the entire range.

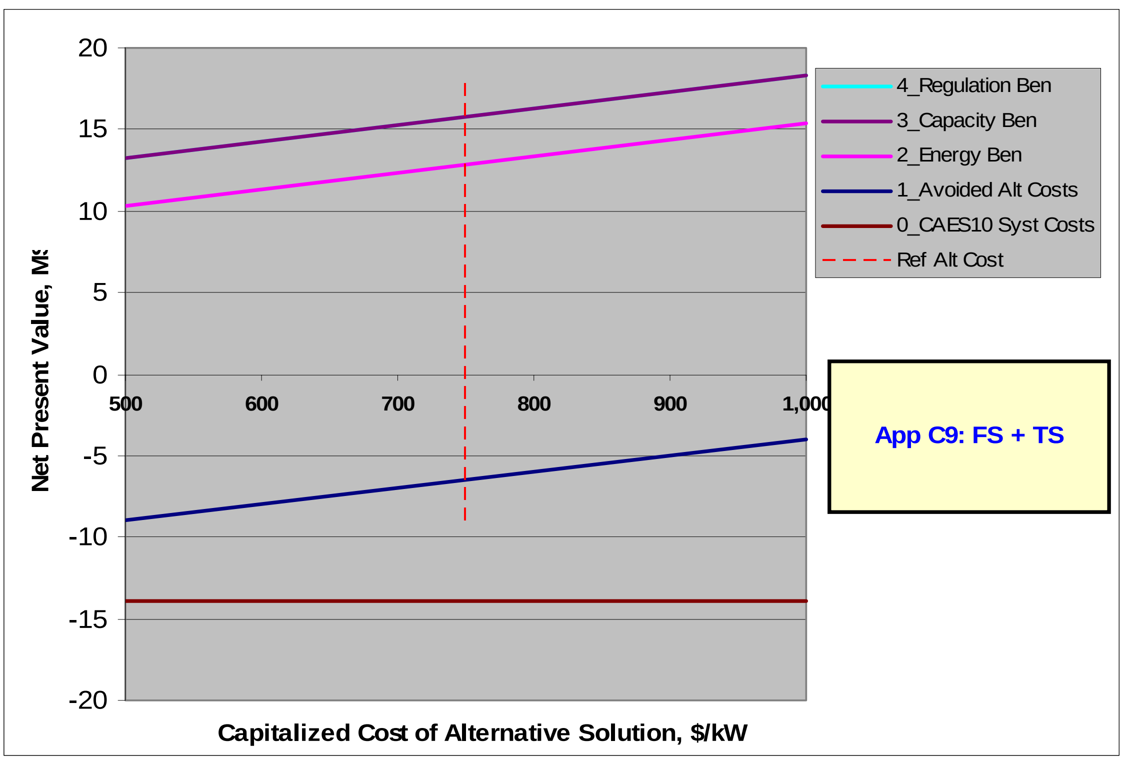

Figure 15-3
Application C9: Small (10 $MW_{ac,}$ 10-Hr Storage) CAES System NPV vs Cost of Alternative Solution

Assessment of Large (300 MW_{ac}) CAES Systems for Wind Applications

Large CAES systems are currently being marketed with one or more turbine systems in the range of 135 MW_{ac} and 300 MW_{ac}. While the reference power was chosen to be 300 MW_{ac}, the results of calculations presented herein apply to both when expressed on a per unit basis (e.g., $/kW, $/kWh). The reference stored energy for large CAES is 40 hours discharge duration for TC applications and 10 hours for TS and FH applications.

Large (300 MW_{ac}) CAES System Compliance with Application Requirements

The large CAES system performance parameters discussed earlier were used to develop approximate sizes and operational parameters for systems meeting the application requirements for the selected CAES applications described in the previous section. Performance aspects of CAES systems for the selected applications are described below and summarized in Table 15-6.

- Application J: Transmission Curtailment (TC) – This application requires that the system store energy when wind generation exceeds transmission capacity in accordance with Texas wind profile. Response within minutes is required. The CAES system for this application optimized for 40 hours storage for a duty cycle equivalent of 52 days per year.
- Application K: Time-Shifting (TS) – This application requires that the system store off-peak wind and purchased energy for discharge during the on-peak interval in accordance with NREL wind profile. Response within minutes is required. The CAES system for this application optimized for 10 hours storage for a duty cycle equivalent of 350 days per year.
- Application L: Forecast Hedge (FH) – This application requires that the system supply stored energy to supplement wind generation upon demand in accordance with NREL wind profile. Prompt system response is required. The CAES system for this application is sized for 10 hours storage for a duty cycle equivalent of 240 days per year.
- Application C6: Combined Applications J, D (TC + RC) – This application requires that the system store energy when wind generation exceeds transmission capacity, plus provide regulation control. Response within minutes is required. The CAES system for this application optimized for 40 hours storage for a duty cycle equivalent of 52 days per year for TC functions, and is assumed to provide RC for 20 hours per day, 350 days per year.
- Application C7: Combined Applications K, D (TS + RC) – This application requires that the system store wind generated or purchased energy during the off-peak period for discharge during the on-peak period, plus provide regulation control. Response within minutes is required. The CAES system for this application optimized for 10 hours storage for a duty cycle equivalent of 350 days per year for TC functions, and is assumed to provide RC for 20 hours per day, 350 days per year.
- Application C8: Combined Applications L, D (FH + RC) – This application requires that the system store wind generated in excess of the bid amount, and/or purchased energy during the off-peak period, for use in mitigating shortfalls in the 3-hour ahead bid forecast market , plus provide regulation control. Prompt system response is required. The CAES system for this

application is sized for 5 hours storage for a duty cycle equivalent of 240 days per year, and is assumed to provide RC for 20 hours per day, 350 days per year

Table 15-6
Large (300 MW_{ac}) CAES System Compliance with Application Requirements

	Single Function			Combined Functions		
Applications	**App J: TC - Avoided Xmsn Curtailment, TX Wind**	**App K: TS - Time Shift, NREL Wind**	**App L: FH - Forecast Hedge, NREL Wind**	**App C6: TC + RC**	**App C7: TS + RC**	**App C8: FH + RC**
Storage Designation	300MW-40h	300MW-10h	300MW-10h	300MW-40h	300MW-10h	300MW-10h
Power Plant						
Combustion Turbine	CT					
Duty Cycles						
Generation Shifting (TC, TS or FH)						
Power, MW	300	300	300	300	300	300
Hours per day, hr	40	10	5	40	10	5
Days per year, days	52	350	240	52	350	240
Load Shift Energy, MWh/yr	783,058	1,314,000	449,441	783,058	1,314,000	449,441
Regulation Control (RC)						
Power, MW				300	300	300
Hours per day, hr				20	20	20
Days per year, days				350	350	350
RC, MW-Hours/yr				2,100,000	2,100,000	2,100,000

Benefit and Cost Analyses for Large (300 MW_{ac}) CAES

CAES Pricing and Integrated System Costs

The installed costs for a 300 MW_{ac} CAES system with 10 and 40 hours storage in a subterranean geologic formation, e.g., a salt dome, are $158 and $174 million, respectively. Capital and operating costs are summarized in Table 15-7, where initial costs include acquisition, space and installation costs; fixed O&M costs include projected annual costs for parts and labor, plus property taxes and insurance; and variable O&M costs include costs for fuel and other variable consumables.

Table 15-7
Capital and Operating Costs for Large (300 MW_{ac}) CAES Systems

Applications	Single Function			Combined Functions		
	App J: TC - Avoided Xmsn Curtailment, TX Wind	App K: TS - Time Shift, NREL Wind	App L: FH - Forecast Hedge, NREL Wind	App C6: TC + RC	App C7: TS + RC	App C8: FH + RC
CAES Storage Capacity, MWh_{ac}	12,000	3,000	1,500	12,000	3,000	3,000
CT Initial Cost, $/kW	300	300	300	300	300	300
BOP Initial Cost, $/kW	210	210	210	210	210	210
CAES Storage Initial Cost, $/kW	70	18	18	70	18	18
CAES Storage Cost, $/kWh	1.8	1.8	3.5	1.8	1.8	1.8
Total Capital Cost, M$	174.0	158.3	158.3	174.0	158.3	158.3
O&M Cost – Fixed, $/kW-year	24.6	23.6	23.6	24.6	23.6	23.6
O&M Cost– Variable, $/kW-year	7.8	13.1	4.5	18.3	23.6	15.0

Note: The total initial cost may be calculated in two ways:
1. By mutiplying the sum of PCS, BOP and Battery initial costs expressed in $/kW by the reference power,
2. OR by mutiplying the sum of PCS and BOP expressed in $/kW by the reference power and then adding the product of Battery Initial cost expressed in $/kWh and the Battery Capacity

As a rule of thumb for a "generic" CAES plant, the operating cost per kWh delivered during power generation mode is the factor "K" times that of the incremental cost per kWh of off-peak power purchased during the compression mode, plus the cost of the fuel (in $/MMBtu) times the plant heat rate, "H_R". For the purposes of evaluating 300 MW_{ac} CAES configuration, K and H_R have been defined as 0.80 and 4500 Btu/kWh, respectively, i.e.: [1, 5]

Cost of electricity generated ($/kWh) = (0.80) (Incremental cost of electricity purchased, $/kWh) + (Cost of fuel purchased, $/MMBtu) (4,500 Btu/kWh) / (1,000,000 Btu/MMBtu)

The factor, K, includes the ratio of generated electricity to purchased electricity and the energy lost to pipe friction, air leakage, pressure regulation, and compressor/expander component efficiencies. The heat rate, H_R, is typical for an expander-generator set operating without the compressor during the generation mode.

For 300 MW_{ac} CAES, fixed O&M costs are based on $13/kW-year, plus property taxes and insurance; and variable O&M costs are based on $0.003/kWh, plus fuel costs calculated for a heat rate of 4,500 Btu/kWh and natural gas fuel priced at $5/MMBtu [1, 5].

Lifecycle Benefit and Cost Analysis for Large (300 MW_{ac}) CAES Systems

Lifecycle cost analyses of large CAES systems using NPV methodology were conducted in the same manner as was done for small CAES systems in the previous section.

The results of lifecycle cost benefit analyses of select CAES applications are summarized in Table 15-8 and discussed below. The bases and methodology used in valuing energy storage applications are described in detail in Chapter 4. The details of the cost benefit analysis for each application are discussed below.

Table 15-8
Summary of Benefit and Cost Analyses of Large (300 MW_{ac}) CAES Systems

	Single Function			Combined Functions		
Applications	App J: TC - Avoided Xmsn Curtailment, TX Wind	App K: TS - Time Shift, NREL Wind	App L: FH - Forecast Hedge, NREL Wind	App C6: TC + RC	App C7: TS + RC	App C8: FH + RC
Alt Solution Value, $/kW	750	0	0	750	0	0
Initial Installed Cost, M$	174	158	158	174	158	158
Total Costs, M$	(273.2)	(270.5)	(244.0)	(305.3)	(302.6)	(276.1)
Total Benefits, M$	550.7	839.5	486.4	893.2	1,182.0	828.9
Benefit to Cost Ratio	2.0	3.1	2.0	2.9	3.9	3.0
NPV, M$	277.5	569.0	242.4	587.9	879.4	552.8

- Application J: Transmission Curtailment (TC) – This application was evaluated on the assumption that transmission upgrade to avoid curtailment can be obtained for net capitalized costs of about $750/kW, including acquisition, fixed and variable O&M, and property taxes and insurance costs, but excluding incremental revenue from avoided curtailment. As described in Chapter 4, energy storage value is derived from energy storage costs plus the difference between the value of revenue from the transmission upgrade solution and the energy storage solution. As shown in Table 15-8, this application yields a NPV of $277.5 million for an initial investment of about $174 million, corresponding to a total benefit to cost ratio of 2.0. As a measure of the sensitivity of NPV with respect to transmission upgrade costs, Figure 15-4 illustrates the change in NPV over a range of $500 to $1000/kW and shows that large CAES systems with 40 hours storage compete favorably with alternative solutions over this entire range.

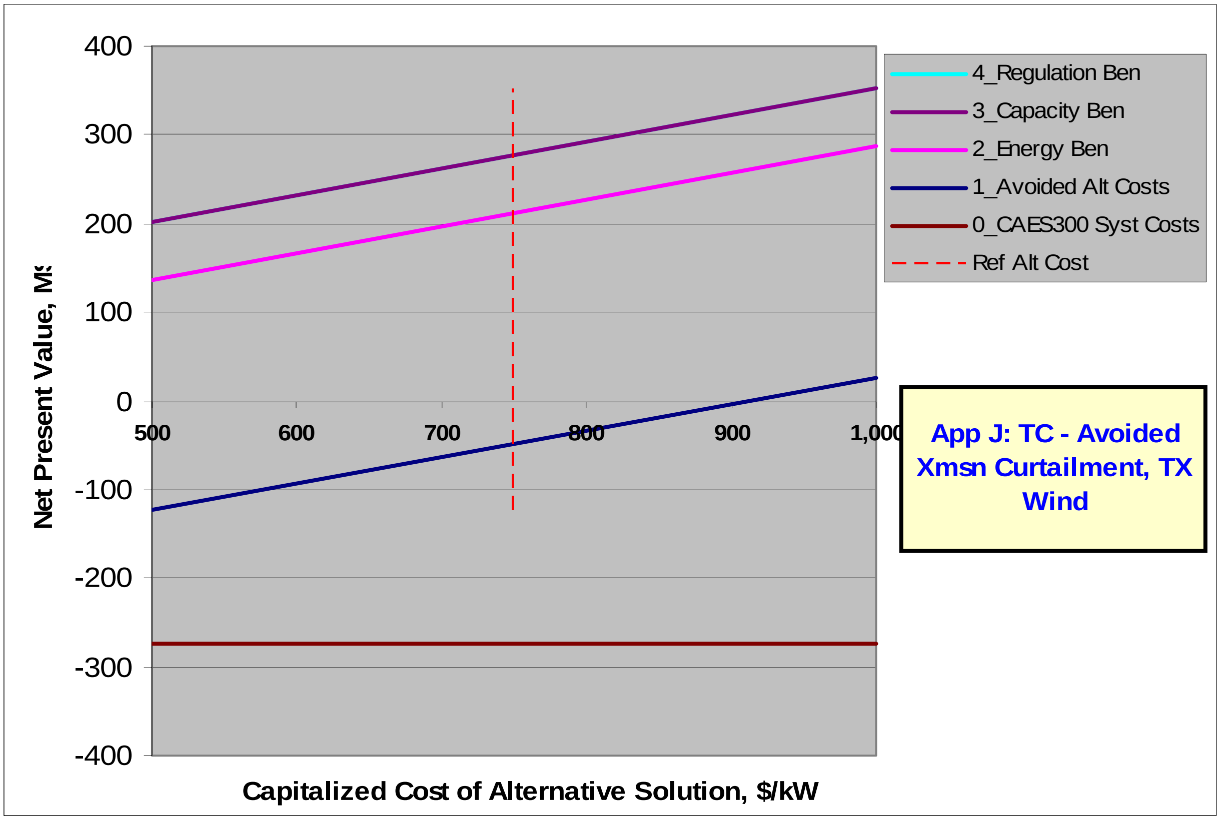

Figure 15-4
Application J: Large (300 MW_{ac}, 40-Hr Storage) CAES System NPV vs Cost of Transmission Upgrade

- Application K: Time-Shifting (TS) – This application was evaluated on the assumption that an alternative solution capable of acquiring on-peak generation at market rates can be obtained. As shown in Table 15-8, this application yields an NPV of $569 million for an initial investment of about $158 million, corresponding to a total benefit to cost ratio of 3.1.
- Application L: Forecast Hedge (FH) – This application was evaluated on the basis of avoided risks associated with market rates and penalties for wind generation bid into the 3-hour ahead electricity market as described in Chapters 3 and 4. As shown in Table 15-8, this application yields an NPV of $242.4 million for an initial investment of about $158 million, corresponding to a total benefit to cost ratio of 2.0.
- Application C6: Combined Applications J, D (TC + RC) – This application was evaluated on the assumption that an alternative solution capable of mitigating TC events can be obtained for net capitalized costs of about $750/kW, including acquisition, fixed and variable O&M, and property taxes and insurance costs plus the value of regulation control at market rates. As shown in Table 15-8, this application yields an NPV of $587.9 million for an initial investment of about $158 million, corresponding to a total benefit to cost ratio of 2.9. As a measure of the sensitivity of NPV with respect to alternative solution costs, Figure 15-5 illustrates the change in NPV over a range of $500 to $1000/kW, as well as the incremental value of regulation control, and shows that CAES systems will compete favorably over the entire range.

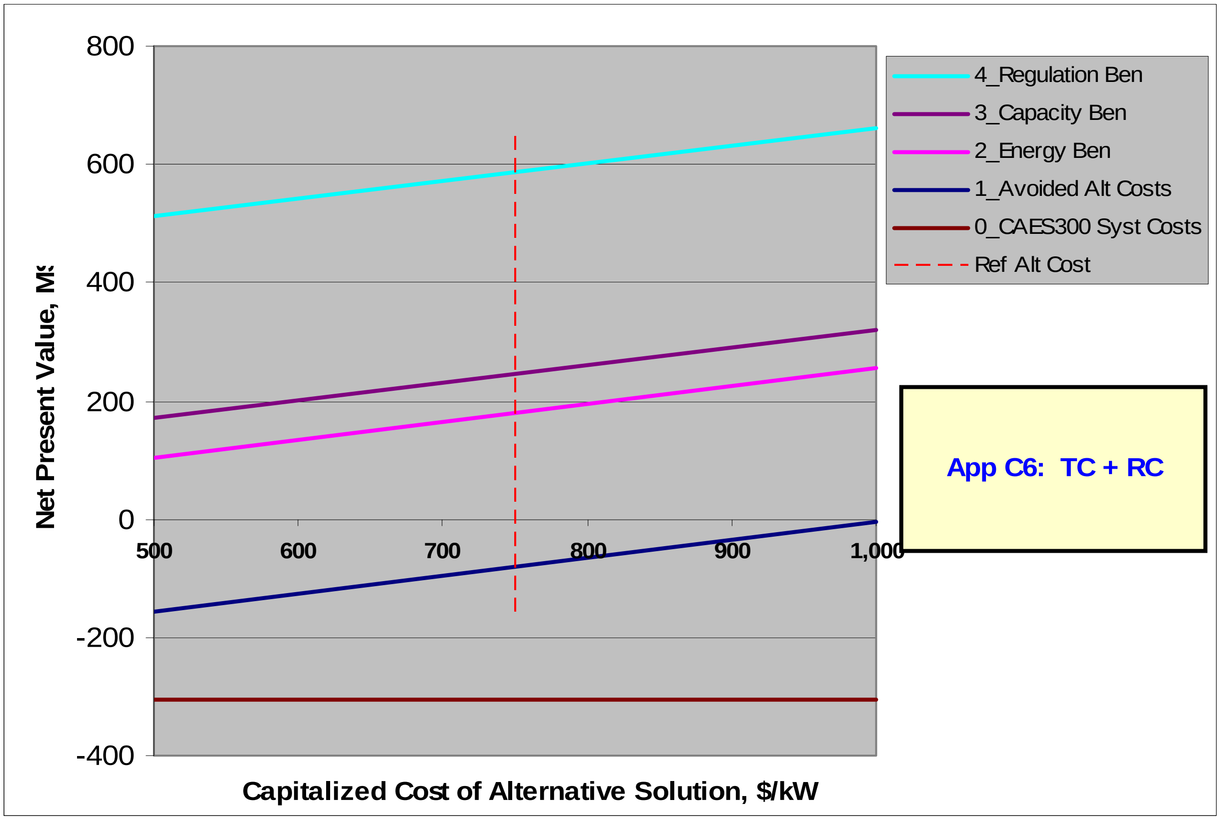

Figure 15-5
Application C6: Large (300 MW_{ac}, 40 Hr Storage) CAES System NPV vs Cost of Alternative Solution

- Application C7: Combined Applications K, D (TS + RC) – This application was evaluated on the assumption that an alternative solution capable of supplying peaking generation can be obtained for net capitalized costs of about $750/kW, including acquisition, fixed and variable O&M, and property taxes and insurance costs, plus the value of regulation control at market rates. As shown in Table 15-8, this application yields an NPV of $879.4 million for an initial investment of about $158 million, corresponding to a total benefit to cost ratio of 3.9.
- Application C8: Combined Applications L, D (FH + RC) – This application was evaluated on the basis of avoided risks associated with market rates and penalties for wind generation bid into the 3-hour ahead electricity market as described in Chapters 3 and 4, plus the value of regulation control at market rates. As shown in Table 15-8, this application yields an NPV of $552.8 million for an initial investment of about $158 million, corresponding to a total benefit to cost ratio of 3.0.

Interpreting Results From Benefit-Cost Analyses

In general, both small and large CAES are very attractive for all single and combined applications without the need for prompt response. However, Application J, Transmission Curtailment, only becomes attractive with more than about 12 hours storage. In this case, small

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CAES is only marginally competitive with 12 hours pipeline storage, while large CAES is very attractive with 40 hours salt dome storage.

The reader is reminded that the foregoing analyses are intended as a guide to the initial consideration of energy storage options, and that these analyses are based on representative electric rates and costs for alternative solutions as described in Chapter 4. The assumptions used herein should be reviewed in light of project specific applications, alternative solutions, electric rates and financial parameters.

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