Wind Power Integration: Energy Storage for Firming and Shaping

Technical Report

Wind Power Integration: Energy Storage for Firming and Shaping

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PRODUCT DESCRIPTION

With the rapid growth of wind power generation, utility systems are beginning to experience the intermittent and variable nature of wind resources in electricity transmission and distribution system operations. Both short-term power fluctuations resulting from gusty winds and longer term power output variations resulting from diurnal wind speed variations and shifting weather patterns can affect utility power delivery as well as grid operations. This report addresses the longer-term power variations of wind power plants and the potential for energy storage to play a role in wind power integration. The related topic of smoothing short-term wind power fluctuations is addressed in a companion report, *Wind Power Integration: Smoothing Short-Term Power Fluctuations* (EPRI report 1008852).

Results & Findings

The application of energy storage can ease wind integration issues and add value to wind energy. However, energy storage systems are typically a relatively large investment and will probably need to solve more than one problem to be cost effective, for example, a case where a single storage application could reduce curtailments, support arbitrage in energy markets, and mitigate ramping at the same time.

Selection of the most appropriate storage technology is decidedly case-dependent. Wind system characteristics, power system integration needs, and the specific application will determine if energy storage is needed. Only four energy storage technologies are attractive at present for wind applications. These are pumped storage, compressed air, sodium-sulfur batteries, and vanadium redox flow batteries.

Challenges & Objectives

The overall objective for this report is a best-practices guideline document that provides a framework for evaluating the engineering and economic feasibility of integrating wind generation and energy storage. The guide is intended to be a transparent methodology for evaluating the technical requirements, benefits, and costs of integrating wind generation and energy storage to address wind energy intermittency and fluctuating output resulting from short-term and diurnal wind speed fluctuations and shifting weather patterns. The input data considered by the methodology include wind resource characteristics, wind plant and turbine design, grid design and operations, energy storage efficiency and cost, and other technical and economic parameters.

Applications, Values & Use

At present there are only a few applications of energy storage in wind generation. Integrating wind and energy storage is certainly in the early application stage, and best practices will continue to evolve. The methodology and comparisons provided here are intended to promote a careful look at wind and storage and to help avoid undue investigation into applications and scenarios that are not cost effective or practical.

EPRI Perspective
When wind generation contributes more than a few percent of the total generation mix, it can affect generation planning and grid operations. Wind intermittency can also affect operating costs of the grid and the value of wind energy in many economic dispatch scenarios. EPRI recently completed several studies that review and update the state-of-the-art in available energy storage technologies for T&D and for renewable energy applications—see EPRI report 1008703 for a summary of recent work. It is clear that several of these new technologies, combined with power electronics, can overcome most of the integration issues for wind power and may tip the scale between successful and unsuccessful integration by mitigating the impacts of unpredictable and intermittent generation. In addition, integration of wind with existing hydroelectric generation provides a low-cost opportunity to store excess wind energy and absorb short-term energy fluctuations in the hydro system. This report is one of several EPRI reports, including *Wind Power Integration Technology Assessment and Case Studies* (EPRI report 1004806), that address technology and applications that will ease the integration of wind power systems into the electric grid. Wind energy forecasting is also an important developing technology for integrating wind energy with hydro and energy storage resources and is addressed in *Wind Energy Forecasting Applications in Texas and California* (EPRI report 1004038) and other recent EPRI reports.

Approach
Several new battery technologies, including flow and hybrid designs, may help level and arbitrage wind-power intermittency. Flywheels and ultracapacitors combined with power electronics, though developed primarily for power quality applications, offer short-term stabilization that can mitigate wind power fluctuations. Power electronics alone or built into wind turbines also offers rapid response and reactive power control that can ease wind power integration in certain utility grid scenarios.

Keywords
Wind Power
Diurnal Variations
Ramping and Regulation
Energy Arbitrage
Storage Batteries
CAES and Hydro
Energy storage

ABSTRACT

With rapid growth of wind power generation, utility systems are beginning to feel the intermittent and variable nature of wind resources in electricity transmission and distribution system operations. Both short-term power fluctuations resulting from gusty winds and longer term power output variations resulting from diurnal wind speed variations and shifting weather patterns can affect utility power delivery as well as grid operations. This report addresses the longer-term power variations of wind power plants and the potential for energy storage to play a role in wind power integration.

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1
INTRODUCTION

Wind power is the fastest growing source of electricity in the world. The rated capacity of installed wind generation reached nearly 46,000 MW worldwide during 2004, and is expected to reach 80,000 MW by 2007 and 175,000 MW by 2012. Development in the United States has accelerated in the past decade, and is expected to continue to grow into the future. With rapid growth of wind power generation, utility systems are beginning to feel the intermittent and variable nature of wind resources in electricity transmission and distribution system operations.

Both short-term power fluctuations resulting from gusty winds and longer-term fluctuations resulting from diurnal wind speed variations and shifting weather patterns can affect utility power delivery as well as grid operations. When wind generation contributes more than a few percent of the total generation mix, it can affect generation planning and grid operations. Wind intermittency can also affect operating costs of the grid, and the value of wind energy, in many economic dispatch scenarios.

Most utility industry engineers believe that the growth in wind power generation will be limited because the intermittent nature of wind energy resources can affect the reliability, reserve and other system requirements, and operating costs of the electricity system. While some level of short- and long-term output variation can be absorbed in most power systems, technical and economic consequences will certainly amplify with higher relative power levels. Large variations in output can create grid operating problems particularly when wind power plants are located remotely and away from load centers. These variations will vary on the basis of duration or rate of change from seconds to hours. The appropriate coping strategies and/or compensation equipment will depend on the time domain of interest.

The expected 30 to 40% capacity factors of wind power become more difficult to manage as wind power levels increase. Consequently, it is important to identify and apply wind integration technologies that will complement integration into the electricity grid. The application of energy storage technologies is one approach that holds great promise for mitigating both short- and long-term difference between system load and generation. However, to date, the persistent high cost of electrical storage (both $/kW and $/kWh) has limited most applications in utility systems.

This report addresses the longer-term variations of wind plant output of wind power plants and the potential for energy storage to play a role in wind power integration. The related topic of smoothing short-term wind power fluctuations is addressed in a companion EPRI report, *Wind Power Integration: Smoothing Short-Term Power Fluctuations* (EPRI report 1008852) March 2005. The two reports distinguish and separately address output intermittency (energy variation) and stabilization (power fluctuation) issues in wind power applications.

Background

Wind power has several unique characteristics which make it substantially different from other forms of generation. The most obvious difference lies in the prime mover, the wind. Wind is a relatively inconsistent prime mover, and is given over to occasional gusts and stills, as well as ebbing and flowing in diurnal patterns.

In addition, the installation of wind generation has naturally followed the areas in which wind resources are most available, and has resulted in the concentration of large blocks of wind generation in inland, coastal, and even offshore areas. Such blocks are relatively large enough to substantially affect grid operations in their vicinity. These effects will only grow to be more significant as wind generation becomes a larger part of the total installed electricity generation on the grid.

Recognizing both the positive aspects of wind generation and its potential to affect grid operations, utilities and system operators are actively evaluating a number of techniques to mitigate the negative impacts of these characteristics. The detailed nature of the problems, as well as an overview of the solutions, has been discussed in a previous EPRI Study, *Wind Power Integration Technology Assessment and Case Studies*, 1004806, March 2004.

Energy storage technology has perhaps the greatest potential to solve wind integration issues. The addition of storage can put wind energy more on par with the value of energy from traditional generation. Properly sized, energy storage can address wind energy intermittency and ramping concerns. Energy storage with fast output power control can also meet the power system's reactive power needs and reduce concern about fluctuating wind output. Remote wind locations with constrained transmission lines can be better utilized when energy storage allows scheduling of power flows when transmission capacity is available.

Table 1-1
Wind Power Issues That May Be Solved With Short-term or Long-term Energy Storage

Wind Power Integration Issue (time frame)	Long-Duration Energy Storage	Short-Duration Energy Storage
Intermittency (minutes to hours)	Can solve	Minimal effect
Ramping Burdens (minutes)	Can help[1]	Can help[1]
Fluctuating Output (seconds)	Can solve[2]	Can solve
Limited Reactive Power (continuous)	Can solve[3]	Can solve[3]
Distributed Collection (n/a)	Minimal effect	Minimal effect
Remote Locations (n/a)	Can help[4]	Minimal effect

[1] Energy storage must operate on a time-scale of minutes to solve ramping

[2] Requires response time on the order of seconds

[3] Assumes energy storage system includes a 4-quadrant inverter

[4] Involves rescheduling power delivery to minimize transmission constraints

Despite this potential, energy storage comes coupled with a major obstacle: cost. There are also application challenges for optimizing the power and energy requirements for each specific situation. Of the various viable storage technology options, each has its advantages and disadvantages in a wind application. For example, large-scale solutions such as pumped hydro storage and compressed air energy storage are economically preferred to smaller solutions, but can be very difficult to site. Smaller scale solutions such as batteries may be easier to site, but will be more expensive.

In 2003, EPRI and the U.S. Department of Energy (DOE) co-sponsored the development of a new reference examining the use of energy storage technologies in utility applications, particularly transmission and distribution applications. The resulting work was released in December 2003 as the *EPRI-DOE Handbook.*[1] The Handbook describes the value of energy storage in the T&D areas, with an approach for judging applications and benefits. It also includes descriptions of those energy storage technologies that have reached a level of maturity and commercialization that puts them within the realm of consideration for such application. Each technology description includes detailed technical discussion, a catalog of past field demonstrations, applications analysis, and cost/benefit analyses for applications and sets of combined applications.

In 2004, EPRI developed a supplement for the handbook to describe the value of applying energy storage to grid-connected wind generation. The handbook supplement[2] and this document, *Wind Generation Integration with Energy Storage*, were developed in parallel as descriptions to this expanding area, and are designed to be complementary documents. The handbook supplement describes cost and benefit analyses for the use of particular types of energy storage with wind generation, while this document explores the best practices for selecting energy storage and actually integrating it with wind generation.

Approach

Wind power variations range from seasonal and day-to-day to power changes over minutes and even seconds to second. In terms of power output these short-term variations are better characterized as variable power, measured in kilowatts or as a power rate of change, measured in kW per unit time. In terms of energy output, long-term variations from a wind plant are best characterized in terms of kilowatt-hours. Over a long period of time they may be described as wind plant availability. That is, on an annual basis, a particular wind plant may provide near rated output approximately 30% of the total time. This is a measure of its energy production rather than power output.

The approach taken in this project has been to evaluate wind power and energy storage practices by separating the distinct issues of power and energy. In both cases power electronics and energy storage technologies may complement wind integration. The devices that are available, the cost-benefit analyses, and relevant application cases depend very much on whether the main issue is power or energy. Consequently, two reports, one on long-term energy concerns, and

[1] *EPRI-DOE Handbook of Energy Storage for Transmission and Distribution* Applications, EPRI Palo Alto, California, 1001834, December 2003.
[2] *Energy Storage for Grid-Connected Wind Generation Applications*, EPRI Palo Alto, California, 1008713, Technical Update December 2004.

another on short-term power issues, have been prepared for wind power applications. Both are intended to provide engineering and economic analysis techniques and recommend practices for solving wind integration problems.

With respect to both power and energy concerns for wind generation the existing condition and configuration of the power system is a critical to determine the ease or difficulty of integration. Depending on the location and other factors a power system may easily integrate wind power or it may have very limited capacity for wind. Energy storage is usually an effective solution for limited capacity situations. Several typical wind scenarios that would clearly benefit from energy storage are listed below:

- Wind power located on power islands or in weak power networks
- Wind power in regions of constrained transmission
- Wind power located in areas with energy markets in which ancillary services or opportunities for arbitrage allow additional value streams for storage
- Existing energy storage is available at low cost

Table 1-2
Wind Power Issues and the Application Scenarios Most Likely to Justify Addition of Energy Storage

	Island or Weak Networks	Constrained Trans-mission	Specific Market Structures	Locations with Low-Cost ES[2]
Intermittency	X	X	X[1]	X
Ramping Burdens	X	X	X[1]	X
Fluctuating Output	X		X[1]	
Limited Reactive Power	X		X[1]	
Remote Locations		X	X[1]	

1 Actual payback for storage likely limited to 1 or 2 areas in a particularly Market.
2 Examples are existing Hydro or batteries, good area for pumped storage or CAES

Integrating wind and energy storage is only in the early application stage, therefore best practices will continue to evolve. The objective for this report is to describe wind generation integration with energy storage in terms of value, design and best practices, which will provide a framework for evaluating the engineering and economic feasibility of such efforts. It documents the technical requirements, benefits, and costs of integrating wind generation and energy storage to address wind energy intermittency and fluctuating output resulting from short-term and diurnal wind speed fluctuations and shifting weather patterns. It shows that wind generation integration with energy storage must take into consideration the wind resource characteristics, wind plant and turbine design, grid design and operations, energy storage efficiency and cost, and other technical and economic parameters.

Contents of This Report

This section addressed the background and approach related to EPRI wind integration efforts and specifically to the application of energy storage for wind. Section 2 of this document describes the various ways in which energy storage can bring value to wind generation plants, with special emphasis on the particular scenarios in which energy storage can be valuable enough to justify its substantial cost.

In Section 3, the most well-known energy storage technologies are investigated for their appropriateness for integration with wind applications. We will discuss the critical parameters that define energy storage as well as describe the principles of operation and the basic performance characteristics of various energy storage technologies. As we will see, some energy storage technologies are more useful than others in conjunction with wind power generation.

Section 4 discusses practices for integrating energy storage with wind generation. This area of research is relatively immature and hence has few precedents on which to base best practices. Nevertheless, an examination of case studies leads us to identify the factors of operation that are most critical in defining the benefits of an energy storage system. We then identify scenarios under which energy storage is most likely to be economically viable, and define a process for analyzing specific cases and locations for which energy storage might make sense.

Section 5 summarizes our discussion and findings, and points the way for further research.

2
THE ROLE OF ENERGY STORAGE

The Functions of Generation

As discussed elsewhere[3], generation in an electric power system functions to produce electric energy to serve the power system load. Generation may include regeneration from stored energy. Electric power systems are fundamentally different from other utilities in two aspects:

- Electric energy is not typically commercially stored like natural gas and water are. Production and consumption (generation and load) must be balanced in near real-time.
- The transmission and distribution network is primarily passive, with no control over the direction of electrical power flows. Flow-control actions are limited to adjusting generation output and to opening and closing switches to add, remove, or reroute transmission and distribution lines and equipment from service.

These aspects of power systems have a number of reliability consequences:

- Every action potentially affects all other activities on the power system, so bulk-power participants must be coordinated.
- The failure of a single element can lead to cascading failure of other elements, so that failure of a single element can cause major disruption if not properly managed.
- Current operations often face constraints in operation because of the need to be ready for the next contingency.
- The speed at which electricity travels requires that system operators take action very quickly, often within fractions of a second. This can rarely be done efficiently by human operators, raising the necessity of automatic systems.

Because of these aspects of electric power transmission and distribution, system operators expect electric generation to have certain capabilities to be considered useful. The most important of these capabilities are listed in Table 2-1.

[3] *Wind Power Integration Technology Assessment and Case Studies,* EPRI, Palo Alto, CA: 2004. 1004806

Table 2-1
Functions and Services Provided by Generation[4]

Functions and Services	Short Description	Time Frame
Base load units (non-regulating)	**Energy** (firm) scheduled well in advance, based on availability, price, and long-term contracts.	**Long-term** commitments
Committed units (usually with regulation capacity)	**Energy** (firm) scheduled based on availability and price to meet block load, with LOLE† and load forecasts considered.	Day before plan, **hourly** resolution
Load-following or energy-balancing units	**Energy** ramping to follow the load, met by adjusting generation schedules and the imbalance energy market.	Hourly plan with **5- to 10-minute** resolution
Frequency regulation (regulating reserves)	**Service** provides capacity based on a signal from dispatcher, with AGC†† to meet CPS 1 and CPS2††† and no net energy††††.	Every few minutes, **minute-to-minute** resolution
Reactive supply and voltage control	**Service** of injecting or absorbing reactive power to control local transmission voltages (usually provided with energy).	Continuous with response in **seconds**
Spinning operating reserves	**Service** to provide energy in response to contingencies and frequency deviations.	Begin within **10 sec** full power in **10 min**
Non-spinning operating reserves	**Service** to provide load/generation balance in response to contingencies, not frequency response.	Respond within **10 minutes**
Replacement reserves	**Service** to restore contingency capacity to prepare for the next generation or transmission contingency.	Respond within **60 minutes**, run up to 2 hours
System black start	**Service** to restore all or a major portion of the power system without outside energy after a total collapse.	**As required**

† Loss of load expectation (LOLE) is the probability that a load cannot be served with available generation.

†† Automatic generation control (AGC) is a method for adjusting generation to minimize frequency deviations and regulate tie-line flows.

††† Control performance standards (CPS1 and CPS2) are minute-to-minute and 10-minute average criteria for load frequency control in each control area. These criteria require the control areas to maintain their area control errors (ACE) within tight limits. ACE is measured in MW and is defined as the instantaneous difference between the actual and scheduled interchanges plus frequency bias (imbalances that bias the system toward maintaining 60 Hz).

†††† Frequency regulation service is usually provided from generation that is on-line and delivering some level of base energy power on a full-time basis or scheduled. The service is to increase and decrease power output where the average output over the scheduled period does not change—that is, there is no net change in delivered energy attributed to the frequency regulation service. Consequently, energy-storage devices could provide this service.

[4] Ibid.

As we will see, the nature of wind generation makes it difficult to meet many of these requirements without auxiliary components. Energy storage is one auxiliary component that can help solve this problem.

Wind Generation

Wind generation differs from conventional generation in several important ways:

- Wind power is ***intermittent*** – that is, wind power output depends on the weather, and changes from day to day, hour to hour, and even minute to minute. The power output cannot be fully controlled, and cannot even be reliably predicted at present. As such, wind power is a "use it or lose it" resource.
- Because wind power cannot be fully controlled, other generation sources may be required to ***ramp*** up or down rapidly in response to wind availability, to properly maintain grid frequency stability.
- Wind has a potential to create voltage ***fluctuations*** in the power system, as a result of natural weather and machine conditions.
- ***The reactive power supplied or absorbed by wind generation cannot be fully controlled.*** The reactive power output of a wind generation facility may vary with the real power output.
- Wind power generation is typically accomplished in a ***distributed*** fashion. Wind power is collected by a large number of relatively small turbines spread over a large area, rather than a single large turbine or a small number of large turbines. In the case of large wind farms, the generated power is collected through a dedicated distribution network and then delivered to the transmission grid. In some cases, the power is delivered directly into a distribution system to serve local customers.
- Wind power tends to be ***remote***; that is, wind generation usually occurs relatively far from the load centers. This is because site selection criteria for large wind farms naturally favor locations far from population centers. This is hardly unique to wind power – hydroelectric and coal power plants are also typically situated far from load centers – but wind developments historically have taken into account neither the available transmission capacity to their sites, nor the costs associated with transmission of the power to the market[5].

All of these issues must be addressed before wind power can be successfully used to deliver power to consumers through the transmission and distribution network. Energy storage can play an important role in dealing with these issues.

[5] Ibid.

Energy Storage Applications to Wind Power

Energy storage can help or solve many of the issues related to integrating wind generation resources with traditional transmission and distribution systems:

- By storing wind energy when it is generated and releasing it when it is needed, it can overcome problems associated with intermittency and ramping.
- Equipped with appropriate power and control electronics, energy storage can eliminate voltage fluctuations and supply or absorb reactive power as needed.
- It can help overcome transmission-related limits by storing energy when available transmission is constrained, shifting the power delivery to times when capacity is available.

In addition to addressing the issues associated with wind, energy storage can also provide other benefits to the existing electrical system. Properly configured energy storage can allow arbitrage: buying electricity at low prices during low demand times, and then selling it at high prices during peak demand times. Energy storage can also provide ancillary services such as spinning reserve and regulation control. In many cases, an energy storage plant can serve more than one purpose, increasing its value to the system.

In the next sections, we will explore in detail the various ways in which energy storage can bring value when integrated with wind generation[6].

Curtailment Reduction

Because wind power is not fully controllable, it is possible for the level of wind generated to exceed the system requirement. This can occur when the load is small and the system operator does not wish to curtail other generation, or because of transmission constraints. In these situations, it becomes desirable to curtail wind generation – by feathering turbine blades to reduce the wind power captured by turbines, or by turning turbines out of the wind. The energy that could be captured is lost and cannot be recovered, leading to a financial loss to the developer.

An energy storage system located close to wind generation can capture the extra energy produced by wind generation at these times and deliver it at later times when curtailment is not necessary. This allows the sale of wind power that would otherwise be lost.

[6] The terminology used to describe energy storage applications to wind power generation can vary from study to study. In the interests of consistency, in this report we have used the terminology used in the *EPRI-DOE Handbook Supplement of Energy Storage for Grid-Connected Wind Generation Applications*, EPRI, Palo Alto, CA, and the U.S. Department of Energy, Washington DC: 2004. 1008703.

Note that the curtailment reduction application requires an energy storage device of large energy capacity, several hours' worth at a minimum. If the energy storage device is completely filled, any additional wind energy must be curtailed, and is effectively lost. Furthermore, since energy stored during a curtailment period would be lost anyway, the round-trip efficiency[7] of the energy storage device is not as critical as it is for non-wind-related energy storage applications, such as diurnal energy arbitrage[8].

Time Shifting

Wind generation plants deliver power according to the supply of wind rather than the demand of the power market. If the wind blows when the demand is low, revenue will be less than optimal. If the wind does not blow when the demand is high, an opportunity to deliver power is missed.

Energy storage can simplify these problems by storing energy when it is generated and dispatching it at a time convenient to the generator. This would allow power generated during periods of low demand to be stored for sale at a greater price during periods of high demand. Since this effectively shifts the dispatch in time, this application is called *time shifting*.

Cost-effective time shifting operation requires an energy storage system of several hours' worth of energy to be cost effective. Unlike curtailment reduction, time shifting requires a fairly high efficiency to make economic sense, although not as much as applications such as energy arbitrage[9].

Forecast Hedging

The issue of wind variability is especially challenging in a deregulated environment, in which buyers and sellers must be able to enter into negotiated contracts for the delivery of power, a significant interval prior to the actual delivery. This can be difficult with wind power, since the wind forecasts only provide limited knowledge as to whether the wind will actually be blowing during the contracted period of time, and whether the power generated will be sufficient to meet the contract. A shortfall in power generated will result in penalties for the generator and reduced supply in the market.

Energy storage can allow the generator to cover shortfalls in generation with energy stored from earlier generation, reducing the risk of penalties from inaccurate forecasts. This application can be called *forecast hedging*.

A forecast hedging application requires an energy storage system with several hours' worth of energy, since contracts typically last several hours. High round-trip efficiency is not as critical as for time shifting but must be reasonably favorable for good economics.

[7] Round-trip efficiency is explained in detail in Section 3.
[8] *EPRI-DOE Handbook Supplement of Energy Storage for Grid-Connected Wind Generation Applications*, EPRI, Palo Alto, CA, and the U.S. Department of Energy, Washington DC: 2004. 1008703.
[9] Ibid.

From a technical standpoint, energy storage used for time shifting and forecast hedging makes firm dispatch possible, and allows the generator to dispatch power according to the power usage profile rather than the wind profile. For these reasons, these uses of energy storage are also often called *firming and shaping*[10].

Frequency Regulation

Grid operators maintain grid stability by holding a constant frequency on the grid, thus ensuring that generation and load are balanced. This is accomplished by ramping generation up or down to account for shifts in the system load, usually in a 5-to-10 minute time frame. This operation is known as *frequency regulation*.

Wind generation is not ideal from a ramping standpoint. Ramping up is possible only if wind is available, and ramping down is undesirable since wind power that is not used is lost. In fact, the variability in the wind can actually create stability problems by introducing rapid uncontrolled shifts on the generation side. This can be a serious problem if wind power forms a significant part of the generation on the system, such as on small island systems.

Energy storage systems can mitigate these problems by performing ramping functions, replacing conventional generation. This can be done in one of two ways. In the first, an energy storage device is installed as a standby unit. In the event of a sudden change in the wind power generated, the device releases or absorbs power for a few minutes until more conventional generation can compensate for the change in generation. In this scenario, the energy storage provides power for only a few minutes and does not require a very large cycle life, but would require a short response time. This could be done with large battery systems such as lead-acid or nickel-cadmium batteries.

Alternatively, an energy storage device can be used to absorb all changes in the grid, effectively replacing other regulating generation on the grid network. In this scenario, the energy storage is much more heavily taxed, and requires more energy capacity and cycle life. This type of application requires larger storage systems with long cycle life, such as CAES or pumped hydro systems[11].

Fluctuation Suppression

Rapid changes in wind generation can cause small voltage fluctuations, often called “flicker” for its effect on electric lights, on the electrical grid in the vicinity of wind generation. Voltage fluctuations as small as 1 to 2% of system voltage can cause visible flicker. Wind turbines can cause voltage fluctuations as a result of a number of natural weather and machine conditions, including fluctuations in wind speed, transients when cutting in or out, tower shadow effects, wind shear, and pitching and yaw errors in the blades. The type of generator used in the turbine can also affect the degree to which flicker occurs. Voltage fluctuations that cause flicker can occur on the time scale of 1 to 2 seconds up to several minutes.

[10] Ibid.
[11] Ibid.

Flicker is much less common than it once was. Most modern wind turbines incorporate technologies which ride through short-term variability in the wind, eliminating the flicker problem. Nonetheless, energy storage has been investigated as a potential solution for places in which fluctuations continue to be an issue. Several test installations have been built for this purpose, and have demonstrated the technical feasibility of the application. Fluctuation problems can usually be solved more cost effectively without the use of energy storage, however, especially if corrective measures can be introduced when the wind generation facility is being constructed[12,13].

Combined Benefits

Energy storage is a relatively expensive solution to wind integration issues. Ideally, an energy storage system should provide multiple benefits, including benefits that do not necessarily have a connection to the wind generation. For example, a system designed for time shifting might also be used for frequency regulation when time shifting is not required.

When considering a system with combined benefits, it is important to be certain that the applications do not interfere with each other. In some cases, the technical requirements for operation make it difficult to use two applications simultaneously. Optimizing an energy storage system for time shifting, for example, may make it less than optimal for fluctuation suppression. Supporting both applications may also make the energy storage system more expensive. Each additional benefit gained should outweigh the cost to accomplish it.

Even when multiple applications are built into a system, the operator should keep in mind that trying to achieve all benefits simultaneously is difficult, and may not be economical. For example, the use of an energy storage system for frequency regulation may make it unavailable for forecast hedging, as the frequency regulation application may require the energy storage to operate at 50% state-of-charge while forecast hedging requires it to be fully charged. Using a system for frequency regulation may cause the battery to age prematurely and require replacement. Operating parameters for energy storage devices should be thoroughly analyzed before design is begun, and tested fully after the storage device is built.

Is Energy Storage Vital for Wind Power Generation?

Many investigators of wind power generation believe that energy storage is absolutely necessary for the proper integration of wind power to the grid. Because of its variability, wind power seems less useful than other generation. Energy storage, on the other hand, can make a variable source of power into a dispatchable, controllable, “well-behaved” source that can be integrated to the existing grid network with a minimum of effort.

[12] Ibid.
[13] *Engineering and Economic Evaluation of Wind System Design Innovations for Smoothing Power Fluctuations*, EPRI, Palo Alto, CA: 2005. 1008389

In reality, energy storage is usually unnecessary for proper integration with the grid. Short-term variability, in particular, tends to disappear in actual projects, for a number of reasons. First, for large wind turbine farms, the short-term variability in power delivery is averaged across the entire farm; at these scales, variability between one turbine and the next tend to cancel one another out. Secondly, wind power generation plants are usually small in comparison to the grids to which they are connected, meaning that the size and stiffness of the grid take care of very short-term variability of power output. Finally, many of the newer wind turbine designs incorporate electronic controls and other techniques that reduce the effect of short-term variability in the wind.

Variability at a longer time frame can be handled in the same way that existing variations in the load are handled: through the use of peaking units. If wind power generation begins to fall unexpectedly, peaking units can be brought online to compensate. If the wind returns, the peaking units can be turned off. This is especially effective when hydroelectric power is available, since there are minimum variable costs associated with using it to regulate frequency[14].

If hydroelectric power is not available, other fast-acting resources may be used. While this might get expensive, it may be more cost-effective than an energy storage plant. Energy storage technologies are quite expensive at present levels of technology. As a result, the value brought by their installation does not always justify their cost.

Who Should Invest in Energy Storage?

At first blush, energy storage appears to be an investment to the wind power developer. Certainly, curtailment reduction, time-shifting, and forecast hedging bring their principal value to the generation company, while frequency regulation could be sold as an ancillary service in deregulated markets.

The fact that energy storage is not vital for connecting wind power to the grid, however, implies that wind power developers themselves have little incentive to build energy storage. For example, some regulators have ruled that integration issues are the responsibility of the grid operator, and that wind power developers should not be penalized for the lack of adequate transmission. This means that wind developers are paid for wind generation even if it were curtailed, and that energy storage for transmission curtailment does not make sense for the developer. In this case, the grid operator would have incentive to build the storage system to recover the energy for which they are paying.

Transmission and distribution utilities are also able to take advantage of other compelling benefit streams for energy storage, such as load shifting for asset deferral, which would help to offset the cost of the system. Wind developers cannot realize any gains from such an application. It is also probable that T&D utilities would be more likely to take advantage of ancillary benefits of energy storage such as frequency regulation.

[14] E. Mainzer and L. Felton, "BPA Wind Integration Services and Operating Experience." Proceedings of the 1st Int'l Conference on Integration of Renewable Energy Resources, Brussels, Belgium, Dec. 3 2004.

For these reasons, investment in energy storage systems is more likely to make sense to utilities than to wind developers. Conceivably, a multi-party agreement involving both utilities and wind developers could be made early in the wind development process, to improve integration and provide benefit to both sides. Case studies of previous efforts in this area suggest that this cooperative approach is difficult to actualize.

Application of Energy Storage to Wind Generation

Based on the above discussion, we can draw several broad conclusions about energy storage in wind applications:

1. *Energy storage is not vital to wind integration.* Energy storage usually brings one or more value streams to a wind power project, but it is not technically necessary in the vast majority of cases. In many cases, the benefits may not be sufficient to justify the cost.
2. *Energy storage investors are likely to be T&D utilities.* Under current rules, few of the benefits of an energy storage project accrue to wind developers. It is more likely that T&D utilities will invest in such projects, since they are better able to realize gains as well as take advantage of additional grid-related value streams.
3. *Most applications for energy storage integrated with wind generation require long-duration energy storage systems.* Load-shifting, curtailment reduction, and forecast mitigation require discharge times in hours, while frequency regulation requires power for at least several minutes. Just one application, fluctuation mitigation, requires power for only a few seconds, and it deals with a problem that is usually better addressed by other techniques.
4. *While important, high round-trip efficiency is not as critical in energy storage applications integrated with wind.* In energy arbitrage and similar bulk energy storage applications, round-trip efficiency must be very high for it to make economic sense. This is because the energy input must be paid for during charging. In wind power applications, however, the variable cost of the energy is zero – the wind is free. For this reason, storage systems with slightly lower efficiencies are acceptable.
5. *Combined benefits make a more compelling case for energy storage than single benefits.* Every additional benefit stream helps to improve the cost/benefit ratio for an energy storage plant. For this reason, every available benefit, including those having nothing to do with wind generation, should be included when analyzing an energy storage system.

3
ENERGY STORAGE TECHNOLOGIES

Keeping in mind the conclusions reached about applying energy storage technologies in support of wind generation, we now turn to an examination of the energy storage technologies themselves. In this section, the basic terms of utility-scale energy storage are described, along with the principles of operation and performance characteristics for the major energy storage technologies.

Energy Storage Parameters

Several concepts are used differently for energy storage systems than they are in other parts of the energy industry. For this reason, it is worthwhile to describe these concepts in detail here.

Power Rating and Energy Capacity

The power rating for energy storage systems is measured in kilowatts (kW) or megawatts (MW). Energy storage systems usually have two power ratings, one for continuous operation and another for peak operation. At the continuous power rating, the energy storage system can operate continuously until it runs out of energy. At the peak power rating, the energy storage system can deliver power for only a short period of time before it must return to the continuous rating. The peak power rating is sometimes called the pulse power rating. For most energy storage systems, the peak power rating is several times the continuous power rating.

The energy capacity for energy storage systems is measured in kilowatt-hours (kWh) or megawatt-hours (MWh). The energy capacity is usually specified at the continuous power rating, so an energy storage plant with a continuous power rating of 10 MW and a capacity of 40 MWh is able to deliver 10 MW for 4 hours when fully charged. The energy delivered by an energy storage system may be dependent on the power level at which it operates. For example, a 10 MW/40MWh battery energy storage system may only deliver 20 MWh if discharged at 20 MW, and may deliver 60 MWh if discharged at 5 MW.

Round-Trip Efficiency

There are several ways to measure the efficiency of an energy storage device, but in the utility industry the most commonly used is the *AC round-trip efficiency*. AC round-trip efficiency is the AC energy output of an energy storage system divided by the AC energy input. For example, a 10 MW/40 MWh battery system may require a 50 MWh energy input to go from fully discharged to fully charged. The system can then be discharged to deliver 40 MWh. The efficiency of this system would be 40MWh/50 MWh or 80%.

The efficiency of energy storage systems is affected by a number of different factors. If the energy storage does not operate at the same voltage as the system, losses arise because a transformer must be used. Energy storage systems that store only DC power must include a charger and an inverter to convert AC power to DC power for storage, and then back again for delivery; these power electronics also produce losses. Some energy storage systems have parasitic losses which consume energy while they are standing by. Some technologies have other intrinsic losses, such as the thermodynamic losses in batteries.

Service Life

The useful life of an energy storage system is described in several different ways. A common metric is *cycle life*, which describes the approximate number of charge and discharge cycles that a particular energy storage device can undergo before failure. For many energy storage devices, cycling introduces structural, mechanical and thermal stresses which form the life-limiting factor for the device. For some energy storage technologies, such as electrochemical batteries, cycle life depends on how deeply the battery is discharged from full charge. The deeper the average discharge, the more the battery is exercised and the shorter the life.

Another metric for life is the *calendar life*, which describes the length of time an energy storage device can remain operational before requiring replacement, regardless of whether it has been used. Calendar life is typically affected by operating conditions and environment.

Cycle life and calendar life is sometimes combined into a single figure called *service life*, which describes how long a system is expected to last in a given application and location. An assessment of service life requires an analysis of the number of cycles, the depth of discharge, and the operating environment to find which degradation modes are dominant.

Because the true useful life depends on a large number of variables, it is important to do a service life calculation on any proposed system rather than relying on published cycle life or other metrics. In many instances, the useful life is less dependent on the number of cycles a device undergoes than on other aspects of the application, such as float voltage or operating temperature.

System Cost

The cost of generic energy storage systems follows two metrics: cost per unit power ($/kW) and cost per unit energy ($/kWh). Cost per unit power is used in a manner similar to the way it is used to describe other capital investments in the utility industry. It is defined as the cost per unit of rated power, and can be used with equipment cost, installed cost, or lifecycle cost.

Cost per unit energy is used quite differently than it is used elsewhere in the utility industry. For energy storage, $/kWh describes the *cost per unit of energy storage capacity*. This definition is different from the way the term is commonly used when referring to generation, for instance, where $/kWh describes the *cost per unit of energy delivered*. The result is that the $/kWh figures for energy storage seem unreasonably high to those used to seeing $/kWh figures for generation.

As an example of calculation of cost for an energy storage plant, consider a 200 MW/1200 MWh pumped hydro facility with an installed cost of $300M. The cost per unit power is $1500/kW, while the cost per unit energy is $250/kWh.

Energy Storage Technologies Suitable for Wind Generation Applications

Although countless ways of storing electrical energy have been proposed, only a few have demonstrated significant potential for use in real-life applications. Of those, many are not suitable for the specific requirements of the utility industry. This section provides a brief description of the energy storage technologies that are already used in the utility industry, or that are generally agreed to have significant potential in utility applications, focusing specifically on applications in combination with wind power generation.

Table 3-1 summarizes the viable energy storage technologies, their relevant advantages and disadvantages, and the companies and groups that are developing them.

Table 3-1
Energy Storage Technologies Suitable for Wind Power Integration

Technology	*Advantages*	*Disadvantages*	*Manufacturers*
Vented Lead-Acid Batteries (Default)	Mature and well-known Low initial cost Long calendar life	Short cycle life Relatively intolerant of temperature extremes	Enersys GNB (Exide)
Valve-Regulated Lead-Acid	Low maintenance Low initial cost	Intolerant of temperature extremes Short cycle and calendar life	C&D Technologies Hawker Energy (Enersys)
Vented Nickel-Cadmium	Mature and well-known Long life Relatively tolerant to temperature extremes	Low cell voltage Float effect makes capacity testing difficult	Saft
Vanadium Redox (VRB)	Relatively high efficiency Power and energy rating are independent	Not yet proven for cycle life or maintenance costs High initial cost (at present)	VRB Power Systems
Compressed Air Energy Storage (CAES)	Mature technology High efficiency Long life Low cost for large scale Power and energy independent	Requires suitable site geology May have ramp rate limit Large scale requires large capital investment and collaborations	Alstom Dresser-Rand Sulzer
Pumped Hydro	Mature technology High efficiency Long life Low cost for large scale Power and energy independent	Requires suitable site geology Difficult environmental issues Large scale requires large capital investment and collaborations	Gugler GmbH Sulzer North American Hydro Water Alchemy Harris
Sodium sulfur batteries (NAS)	High energy density High efficiency Long cycle and calendar life	Relatively new and untested, High initial cost (at present)	NGK Insulator
Zinc-bromine batteries	High energy density Flat voltage profile	Relatively unknown and untested May require occasional stripping cycles High initial cost (at present)	ZBB Energy
Superconducting Magnetic Energy Storage (SMES)	High power density High cycle life	Very high initial cost (at present) Low energy density	American Superconductor
Ultracapacitors	High power density High cycle life	High initial cost (at present) Low energy density	Maxwell NESS Capacitor ESMA
Flywheels	High power density High cycle life	Relatively high initial cost per kWH Low energy density	Active Power Beacon Piller
Regenerative Hydrogen Storage	Hydrogen production	Short life (at present) Poor storage density Poor efficiency	

Pumped Hydroelectric Storage

Pumped hydroelectric storage, usually called pumped hydro storage, is the most mature and most common form of bulk energy storage used at the utility scale. Pumped hydro storage stores energy by pumping water from reservoir at lower elevation to a reservoir at higher elevation. The energy is stored in the higher potential energy of the water at the higher elevation. The energy is recovered when the water is allowed to flow back to the lower reservoir through hydroelectric turbines, regenerating the power. A cross-section of a typical pumped hydro plant is shown in Figure 3-1.

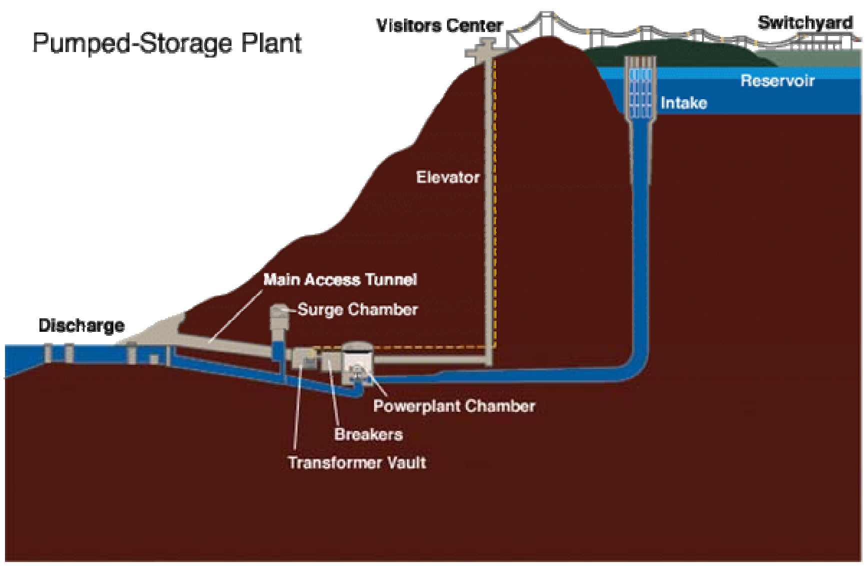

Figure 3-1
Cross-section of a Pumped Hydro Storage Plant (Courtesy Tennessee Valley Authority)

Pumped hydro storage has several technical advantages over other storage technologies. It uses well-understood and generally familiar technology. Utilities are comfortable with the construction, operation and maintenance of hydroelectric turbines, and the principle of pumped hydro storage is a simple one. Utilities that already maintain hydroelectric facilities will already have most of the expertise necessary to operate and maintain a pumped storage facility.

This familiarity has allowed the construction of very large pumped hydro facilities. No other energy storage technology has been successfully implemented on the scale of hundreds or thousands of MW; few have been implemented even on the tens of MW scale.

Another advantage of pumped hydro is the ability to size the facility independently for power and energy. The power rating of a pumped hydro facility depends on the size and number of turbines generating power; the stored energy capacity depends on the water volume and elevation of the upper reservoir. As a result, the energy capacity of a pumped hydro facility is independent of its discharge rate.

Pumped storage also has some disadvantages. Pumped hydro storage has a relatively low energy density, and so is best implemented at relatively large scales. The cost of such projects can be enormous, and the environmental impacts can be significant. The places where such projects can be placed are limited by the local environment, as there must be a significant quantity of water available, and a natural elevation difference is helpful. If no natural elevation is present, one or both reservoirs must be created at a higher elevation – a potentially expensive task.

To offset the large costs of pumped hydro storage, many implementers of pumped hydro storage seek multiple value streams for one or both reservoirs. For example, the upper reservoir in some pumped hydro systems is used for recreation. But other value streams can interfere with the principal energy storage function of the pumped hydro facility. Recreational users may not appreciate the unannounced use of the pumped hydro storage facility.

Compressed Air Energy Storage

Compressed air energy storage (CAES) plants store electrical energy by compressing and storing a large volume of air. The air is stored in underground caverns or aquifers, or in above-ground piping or vessel systems. The energy is recovered by using the air as an input for a turbine-electric generator. Effectively, CAES plants operate by separating in time the compression and expansion stages of the turbine. Figure 3-2 shows an example of a CAES plant designed for electricity arbitrage.

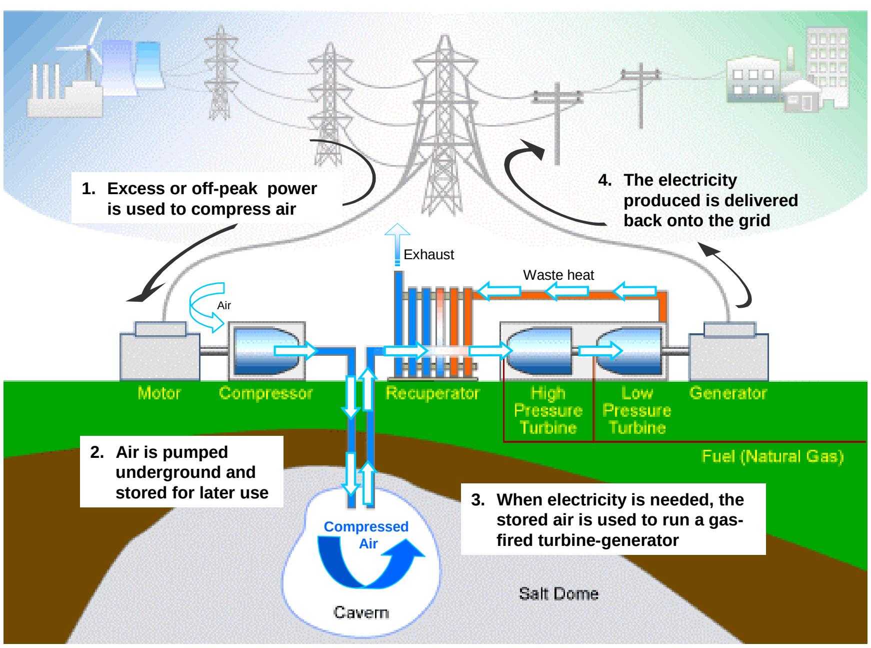

Figure 3-2
Layout and Components of Typical CAES Plant (From Ridge Energy Storage)

CAES technology has several advantages as an energy storage technology. As with pumped hydro storage, the power and energy storage capacity for a CAES facility are independent. The input power rating depends on the size of the compressor, while the output power rating depends on the size of the turbine-generator, and the energy storage capacity depends on the size and pressure rating of the cavern or other air storage system[15]. The scale of CAES technology means that it is usually cheaper in $/kW and $/kWh than other technologies (with the possible exception of pumped hydro), provided a suitable location is found. As a result, it is considered very attractive for integration with wind generation.

Two other aspects of CAES make it different from most other energy storage technologies. Most CAES systems require large air storage containers. The best containers are appropriately-sized caverns or aquifers. As shown in Figure 3-3, there is no dearth of such conditions in the U.S., but a significant amount of time and effort must go into ensuring a site is appropriate and safe for a CAES system.

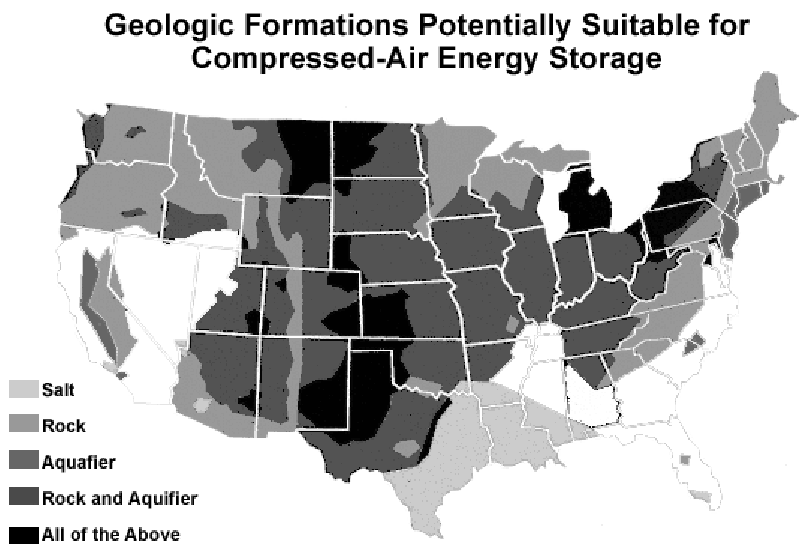

Figure 3-3
Geologic Opportunities for CAES Plant Sites in the Continental U.S.[16]

[15] *Wind Power Integration Technology Assessment and Case Studies*, EPRI, Palo Alto, CA: 2004. 1004806
[16] *EPRI-DOE Handbook of Energy Storage for Transmission and Distribution Applications*, EPRI, Palo Alto, CA, and the U.S. Department of Energy, Washington DC: 2003. 1001834.

In addition, since a combustion turbine is usually used to reconvert the energy stored, most CAES systems require a fuel input during discharge. This unique aspect of CAES has two important ramifications. First, a fuel supply must be accounted for in the CAES analysis. This adds another variable to the economic equation, since the costs of operating the plant may vary dramatically with the market price of fuel. Second, the electrical energy output of a CAES plant is actually greater than the electrical energy it has stored. The additional energy, which comes from the combustion energy of the fuel input, is often called *uplift*. Since round-trip efficiency is calculated as output electrical energy divided by input electrical energy, uplift usually causes the efficiency of CAES systems to be greater than 100%.

Adiabatic CAES systems have also been proposed. These systems would store the thermal energy produced during compression and return it to the air during expansion, eliminating the need for a fuel input during discharge. While several such systems have been analyzed, none have been built.

There are two existing CAES systems. The first, located near Huntorf, Germany, has been in operation since 1978. The Huntorf facility is rated for 290 MW and functions primarily for cyclic duty, ramping duty, and as a hot spinning reserve for industrial customers. Although not originally built to support wind turbines, it has recently been used for leveling the variable power from wind generators in Germany.

The other facility, located in McIntosh, Alabama, has operated since 1991. It provides a variety of services, including load management, ramping, and spinning reserve, as well as operating as a generator of peak power and as a synchronous condenser.

In recent years, a number of CAES projects have been proposed in the U.S., of which three are prominent. The first is the Norton CAES power plant, located in Norton, Ohio. When completed, this plant will be the worlds largest, and will be rated for 2700 MW.

The other two proposed projects are directly related to wind generation. The first is a 540 MW plant proposed for construction in Matagorda in West Texas. The other is a proposal for a 100 to 200 MW CAES plant in north central Iowa, near Fort Dodge. Section 4 describes both projects.

The EPRI-DOE Handbook of Energy Storage for Transmission and Distribution Applications[17] provides a more detailed technical description of CAES and its relative economic value to other energy storage devices.

Electrochemical Batteries

Electrochemical batteries are the oldest, best known, and most widely used form of electrical energy storage. They were first developed in the early nineteenth century, and played an important role in early investigations into electricity.

[17] Ibid.

Batteries store energy in chemical form. An electrochemical cell[18] is composed of two halves, a positive half and a negative half. The positive half contains a positive electrode and a positive electrolyte; the negative half contains a negative electrode and a negative electrolyte. The positive electrode and electrolyte can react with each other to release energy, but only in the presence of a source of electrons that can be supplied to the electrode. Similarly, the negative electrode and electrolyte can react to release energy, but only in the presence of a sink that draws away the excess electrons produced at the electrode.

If the positive electrode and the negative electrode are connected by a conducting wire, excess electrons created by the reaction at the negative electrode can be drawn away to supply the reaction at the positive electrode. This allows both reactions to proceed[19]. The energy released can be harnessed electrically by placing a load in the conduction path between the two electrodes.

The batteries most commonly used in the utility industry are *secondary*, or rechargeable, batteries. In secondary batteries the chemical reactions at the electrode can be run backwards through the application of a current in the reverse direction to the discharge current, absorbing energy in the process. The absorption and release of energy can be done a number of times, until the battery wears out due to chemical or mechanical wear. Secondary batteries are also often called *storage batteries*.

Batteries have the advantage of being familiar and well-understood in application. Because they store energy chemically, they are much more energy dense than devices based on physical processes such as pumped hydro, flywheels, and ultracapacitors. Batteries tend to wear out more quickly than other energy storage devices, however, and are somewhat sensitive to the conditions of use, particularly temperature. In addition, many batteries use environmentally toxic materials such as lead and cadmium, which must be properly disposed of at the end of the project.

Lead-Acid Batteries

Lead-acid batteries represent the oldest and most widely used type of commercial storage battery. The lead-acid cell is composed of a lead negative electrode and a lead oxide positive electrode in a common sulfuric acid electrolyte. They have been in commercial use for well over a century, in applications in every area of the industrial economy. Because of their low cost and ready availability, lead-acid batteries have come to be accepted as the default choice for energy storage in most new applications outside portable electronics. This popularity comes despite many perceived disadvantages, including low specific energy and specific power, short cycle life, high maintenance requirements, and environmental hazards associated with lead and sulfuric acid. Continuous improvements in chemistry, mechanical and electrical design, and operational and manufacturing techniques have mitigated many of these disadvantages, and lead-acid remains the most popular energy storage technology for large-scale applications.

[18] By convention, a cell is defined as a single electrochemical unit consisting of two half-cells, each with its own reaction. A battery is defined as a string of cells connected in electrical series.
[19] The two electrolytes must also be allowed to exchange ions so that the charge is equalized between the two half-cells. This can be done with an ion-conducting material between the two electrolytes. In many batteries, the same electrolyte acts as both positive and negative electrolyte, simplifying the system.

Lead-acid batteries are categorized in several ways: method of electrolyte management (flooded vs. valve-regulated), grid alloys (lead-antimony vs. lead-calcium), application (cranking vs. deep-cycle). The performance can vary greatly between different types, and it is important to get the correct type of battery for a given application.

A number of utility scale projects have been built from lead-acid systems. The best known was a 40 MW plant built in Chino, California by Southern California Edison in the early 90s. The plant was designed to explore the use of energy storage in a number of applications, including load shifting for T&D deferral, frequency regulation, and voltage support. The Chino plant was preceded by several smaller-scale projects, and was followed by the even larger PREPA system at Sabano Llano, Puerto Rico. While most of the lead-acid battery systems were considered technical and economic successes, the initial expense of such plants, their uncertain regulatory status, and the general antipathy of the utility industry towards lead-acid batteries resulted in limited follow-up projects.

Figure 3-4
A Stationary Flooded Lead-Acid Cell (Courtesy C&D Technologies)

Nickel-Cadmium Batteries

Nickel-cadmium batteries are similar in operating principal to lead-acid batteries, but are constructed slightly differently, with nickel oxyhydroxide and cadmium electrodes in a common potassium hydroxide electrolyte. Like lead-acid batteries, they are a relatively mature technology, and can easily be built into relatively large systems. They boast somewhat better cycle life and power performance than lead-acid, but at a considerably higher expense.

The best-known utility project constructed with nickel-cadmium batteries is the Golden Valley Electric Association Battery Energy Storage System (GVEA BESS), completed in 2003 in Fairbanks, Alaska. The GVEA BESS is sized to provide 27 MW for 15 minutes or 46 MW for 5 minutes. It is used primarily for spinning reserve for the Fairbanks region, which receives most of its power from Anchorage area through the Northern Intertie, but is also used to suppress frequency excursions. During a loss of generation or an outage on the Intertie, the battery is designed to provide power for a few minutes until additional generation comes on-line.

Figure 3-5
Battery Banks From the GVEA BESS

Sodium-Sulfur Batteries

Sodium-sulfur batteries are based on a high-temperature electrochemical reaction between sodium and sulfur, separated by a beta alumina ceramic electrolyte. While originally developed for electric vehicle applications, they were adapted for the utility market by the Tokyo Electric Power Company (TEPCO) and NGK Insulators, Ltd., both based in Japan. By the late 1990s, NGK and TEPCO had deployed a series of large-scale demonstration systems, including two 6 - MW, 48-MWh installations at TEPCO substations. In 2002, TEPCO and NGK announced full commercialization of their sodium-sulfur battery line under the trade name NAS, for power quality and load shifting applications. Also in 2002, the first NAS battery was installed in the U.S. at an American Electric Power (AEP) laboratory at Gahanna, Ohio. NAS batteries have also been tested in wind applications, as described in Section 4.

Sodium-sulfur batteries have excellent cycle life and are relatively mature products, with over 55 installations worldwide. As such, they are an excellent candidate for peak shaving and load leveling applications at the distribution level in the near future. The main obstacle to their deployment is the cost; a drop in price is likely to make them very attractive for these applications.

Figure 3-6
NAS Module (Courtesy NGK Insulators, Ltd.)

Flow Batteries

Flow batteries are electrochemical batteries in which the active materials are contained in the electrolyte rather than in the solid electrodes. These electrolytes are stored in tanks sized in accordance with application requirements, and are pumped through reaction stacks which convert the chemical energy to electrical energy during discharge, and vice-versa during charge. Figure 3-7 illustrates the principles of operation for a typical kind of flow battery, the vanadium redox flow battery.

The most important advantage of a flow battery lies in the independent sizing for energy and power. The energy rating of the battery depends on the volume of electrolyte, while the power rating depends on the size of the reaction stacks. A flow battery system can be sized very closely to the requirements of a particular installation, which makes flow batteries especially attractive for long duration discharge applications requiring energy to be delivered for several hours. The nature of flow battery systems makes them particularly suited to large-scale systems, and the electrolyte does not wear out, so that users can expect a relatively long service life. In addition, the flowing electrolyte simplifies thermal management as well as some aspects of maintenance.

With these advantages come some disadvantages. Flow batteries are complex systems with pumps, plumbing, and other auxiliary components, which make them substantially more complicated and prone to leakage than conventional batteries. Flow batteries are a relatively immature technology and have not yet been tested widely.

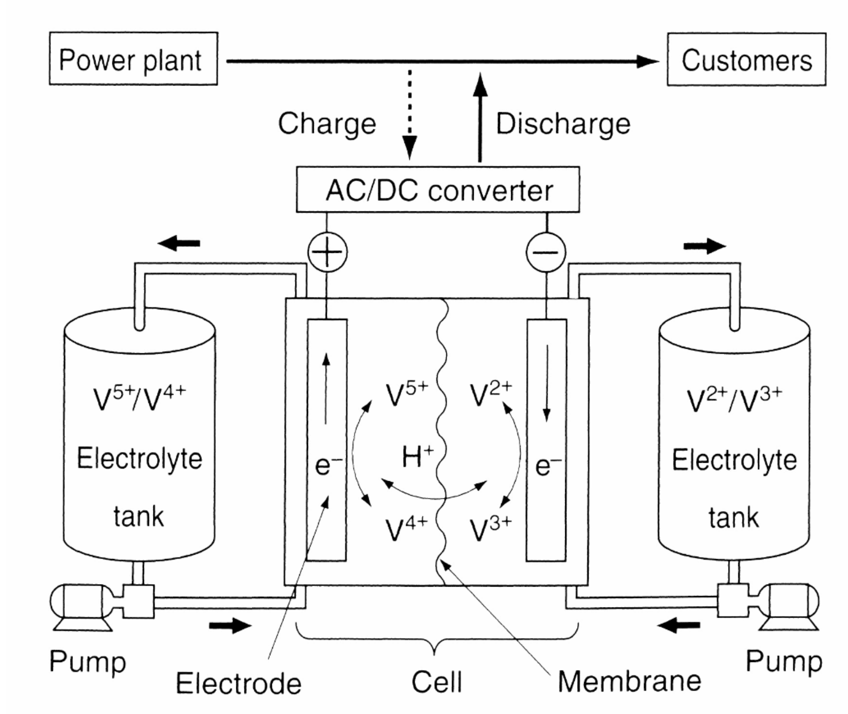

Figure 3-7
Principles of Operation for a Vanadium Redox Flow Battery (Courtesy Sumitomo Electric Industries)

There are several types of flow batteries of which two types are available commercially: vanadium redox flow batteries, and zinc-bromine batteries.

Vanadium Redox Systems Batteries

Vanadium redox batteries (VRB) store energy in electrolytes based on ionic forms of vanadium. At the positive electrode, V^{5+} is converted to V^{4+} during discharge through the acceptance of an electron. At the negative electrode, V^{2+} is converted to V^{3+} through the release of an electron. The reactive species are in solution both before and after the reaction.

There have been several prominent VRB projects at the utility scale. In 2003, PacifiCorp, a utility in the Northwestern U.S., installed a VRB facility on a distribution feeder at Moab, Utah. This facility, constructed by VRB Power Systems Inc., is designed for peak shaving and voltage support functions to defer a feeder upgrade.

In addition, VRB projects have been installed in conjunction with some wind projects. In 2003, a 200 kW vanadium redox flow battery was installed on King Island, Australia, to provide stabilization and time shifting services in connection with a 2450 kW wind installation. The small island of the coast of the Tasmania has a population of about 1,500 and a peak power load of about 3 MW. In this situation, in which a small grid gets significant percentage of its power from wind energy, energy storage has clear value. Section 4 describes this installation in further detail.

Figure 3-8
VRB Battery at Moab, Utah

A similar wind installation, at a larger scale, is planned in Japan. In 2003, J-Power, a Japanese generation utility, announced that it would install a new VRB system at its Tomamae Wind Villa wind farm at Tomamae, Hokkaido. The J-Power installation will consist of a VRB system sized to provide 4 MW for 1.5 hours, or 6 MW for 20 minutes, with an inverter capability of 6 MVA. The main function served by the installation will be power output stabilization and time shifting.

Zinc-Bromine Flow Batteries

Zinc-bromine flow batteries use zinc and bromine ions as the active species. During the discharged state, both species are dissolved in their respective electrolytes, but in the charged state, zinc is precipitated as a solid on the negative electrode. This precipitation aspect makes the sizing of zinc-bromine batteries somewhat more complicated than that of other types of flow batteries. Zinc-bromine batteries still enjoy the other advantages of flow batteries, such as long cycle life and scalability.

Zinc-bromine batteries have been investigated in several utility applications, particularly load shifting for transmission and distribution deferral. In 2001, a 400-kWh zinc-bromine system was tested in Lum, Michigan as part of a project sponsored by the U.S. Department of Energy. The system, manufactured by ZBB Energy Corporation, was installed at a substation at the end of a 4.8 kV distribution line to provide relief to an 800 kVA transformer. The transformer normally operated near capacity, and was expected to exceed capacity during peak hours during the summer months. The system was successfully tested for three months in the summer and autumn of 2001.

Figure 3-9
Zinc-Bromine Battery Installation at Lum, Michigan (Courtesy ZBB Energy Corporation)

In 2004, DOE and the California Energy Commission (CEC) co-funded a new project in California. The project will consist of a 2000 kW / 2000 kWh battery storage system constructed by ZBB Energy Corporation, used in a load-shifting application for the purpose of distribution upgrade deferral. The installation is scheduled for completion in October 2005[20].

Other Flow Battery Technologies

Several other flow battery technologies exist, of which two should be mentioned here. Polysulfide-bromide (PSB) batteries are flow batteries based on a reaction between sodium bromide and sodium polysulfide. PSB batteries were under development by Innogy, a UK subsidiary of RWE, under the brand name Regenesys. Two demonstration sites were planned, one at the Little Barford Power Station in the UK, and the other near Columbus, Mississippi. These plans were halted when RWE withdrew the Regenesys technology from the market in late 2003. In 2004, VRB Power Systems, Inc. licensed the technology from RWE, to continue development efforts with possible reintroduction in several years.

Cerium-zinc flow batteries have been proposed by a company called Plurion Systems, Ltd. According to the company's claims, a cerium-zinc battery would produce a higher voltage than other flow batteries, making it easier to produce a system with workable voltage. As of this writing, Plurion has not yet released a product, and it appears that this technology is still in the early stages of development.

[20] *EPRI-DOE Handbook Supplement of Energy Storage for Grid-Connected Wind Generation Applications*, EPRI, Palo Alto, CA, and the U.S. Department of Energy, Washington DC: 2004. 1008703.

Other Batteries

Other battery chemistries, particularly nickel metal-hydride and lithium ion, have also been proposed for utility scale applications. While many of these chemistries show promise in this application, most have not reached a suitable level of maturity, or are too expensive. For these reasons, there have been no significant field demonstrations of these products. Nonetheless, it is expected that exploration of their use in utility-scale applications will grow in the future.

Flywheels

Flywheels store energy in the angular momentum of a spinning mass. During charge, the flywheel is spun up by a motor with the input of electrical energy; during discharge, the same motor acts as a generator, producing electricity from the rotational energy of the flywheel.

Flywheels have several advantages over electrochemical batteries. Most products are capable of several hundred thousand full charge-discharge cycles and so enjoy much better cycle life than batteries. They are capable of very high cycle efficiencies of over 90%, and can be recharged as quickly as they are discharged. Since the energy sizing of a flywheel system is dependent on the size and speed of the rotor, and the power rating is dependent on the motor-generator, power and energy can be sized independently. The down side to flywheels comes from their relatively poor energy density and large standby losses.

Flywheels have predominantly been used in power quality applications, in which flywheels provide ride-through capability for momentary voltage sags and interruptions. Many systems incorporate both flywheels and generators. The flywheel allows ride-through of interruptions up to about 15 seconds duration. This time also allows enough time for a generator to come on-line for longer interruptions[21].

Short-duration flywheels have also been used to serve fluctuating loads at the distribution level, particularly loads related to mass transit. Electric service to mass transit often experiences load fluctuations related to electric trains leaving and stopping at stations. There is also an opportunity for demand reduction and energy recovery via regenerative braking. Flywheels can be set up on the electric bus serving a mass transit station, so as to accept energy released by the train during a stop, and then release it to accelerate the train as it leaves. This reduces the electric demand on the local distribution system, allowing reduction in substation capacity, better utilization of existing T&D assets, and deferral of construction of new capacity. A prototype system was installed by the New York Power Authority (NYPA) and New York City Transit (NYCT) in 2001. The flywheel system, produced by Urenco Power Technologies, consisted of ten 100-kW flywheels, together storing 5 kWh of electrical energy. The system operated successfully for three years, but was removed because the vendor exited the flywheel market and withdrew their flywheel products from the market.

[21] *EPRI-DOE Handbook of Energy Storage for Transmission and Distribution Applications*, EPRI, Palo Alto, CA, and the U.S. Department of Energy, Washington DC: 2003. 1001834

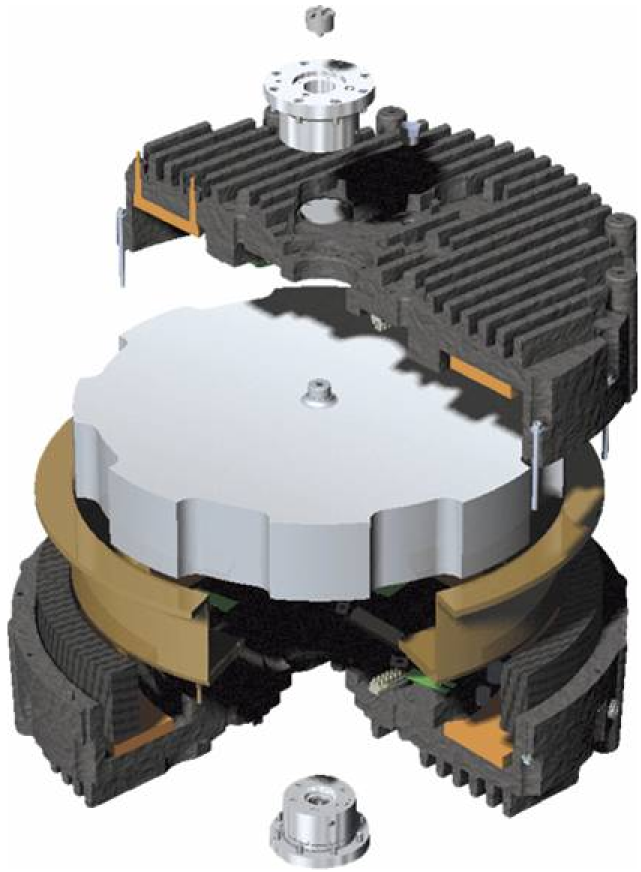

Figure 3-10
Cutaway Diagram of an Active Power Flywheel (Courtesy Active Power, Inc.)

More recently, flywheels have been proposed for longer duration applications. Beacon Power Corporation, a manufacturer of high energy-density flywheels, is proposing flywheels for frequency regulation applications at the transmission level. This application is being tested in upcoming demonstrations in New York, funded by the New York State Energy Research and Development Authority (NYSERDA), and in California, funded by the California Energy Commission (CEC). There are no plans at present to use long-duration flywheels in wind applications.

Ultracapacitors

Ultracapacitors, also known as supercapacitors, electrochemical capacitors, and electric double layer capacitors (EDLC), are devices that resemble very large capacitors in the way they perform electrically. This technology allows capacitors with very high capacitance, measured in farads or even thousands of farads, but at relatively low voltages, between one and three volts. High-voltage ultracapacitor systems consist of multiple individual cells connected in series to produce the desired voltage.

Figure 3-11
ESMA Ultracapacitor

Ultracapacitors are generally characterized by longer cycle life and higher power density than batteries, but much lower energy density. At present, they are also quite expensive and require control and power electronics for proper operation.

Present ultracapacitor products are appropriate for short-duration applications, such as ride-through for power quality.

Investigators have also researched their use for voltage stability in conjunction with Flexible AC Transmission System (FACTS) controllers. This application, similar to the D-SMES technology described earlier, uses real power injection to aid in maintaining voltage stability during a disturbance.

Ultracapacitors have also been used to stabilize voltage in the presence of high power loads, such as the power draw from trains at mass transit stations. This is similar to the mass transit application of flywheels described earlier. The ultracapacitor system captures energy from the braking of a light rail vehicle, and stores it until it is necessary for accelerating a vehicle. This reduces the effect of acceleration and braking on the local electrical distribution system, allowing reduced distribution capacity and better utilization of existing assets[22].

[22] *EPRI-DOE Handbook Supplement of Energy Storage for Grid-Connected Wind Generation Applications*, EPRI, Palo Alto, CA, and the U.S. Department of Energy, Washington DC: 2004. 1008703.

Superconducting Magnetic Energy Storage

Superconducting magnetic energy storage (SMES) devices store energy in magnetic fields produced by continuously circulating current in a superconducting coil. Although it is theoretically possible to use SMES systems for large-scale load shifting applications, such an application would require very large systems, and would not be viable unless the cost of the technology substantially decreases from its present cost. For this reason, SMES technology has been implemented mostly for very short-duration discharges on the order of seconds.

At present, the only commercially available product using SMES is the D-SMES system produced by American Superconductor. This product is designed to provide reactive power for voltage support at the distribution level, with real power injection available to support the line during disturbances. When needed, the D-SMES can deliver 3 MW for 1 second. SMES units have also been used for power quality applications, to allow ride-through of voltage sags for individual customers[23].

Regenerative Hydrogen Storage

Regenerative hydrogen storage has also been proposed as an energy storage mechanism. In this scheme, excess wind power is used to generate hydrogen, which can be used to generate electricity later or as a fuel for vehicles or other applications. The main objection to such a scheme is that the efficiencies associated with hydrogen generation, storage, and conversion back to electricity are relatively poor, at least at the present level of technology.

Regenerative hydrogen storage works in the following way. Excess wind power is used to generate hydrogen through the electrolysis of water. The water decomposes into oxygen, which is released into the atmosphere, and hydrogen, which is compressed and stored. When electricity output is required, the hydrogen is run through either an internal combustion engine or a fuel cell system to regenerate electricity.

While this process works in principle, there are several inefficiencies in the process. At present, electrolyzers have relatively low energy efficiencies. Hydrogen storage is somewhat difficult: the most cost-effective method at present is compressed hydrogen storage, which requires compression of the hydrogen to high pressure. The energy of compression represents another inefficiency. Finally, the reconversion of hydrogen back into electricity also involves losses, since both internal combustion engines and fuel cells have significant losses.

Most components used in this type of system are at a relatively low level of maturity. While this means that there is significant potential for improvement, it also means that systems can be expensive while reliability can be somewhat poorer than desirable, especially at large power levels. For these reasons, regenerative hydrogen storage does not appear to be a viable energy storage mechanism at present.

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[23] *EPRI-DOE Handbook of Energy Storage for Transmission and Distribution Applications*, EPRI, Palo Alto, CA, and the U.S. Department of Energy, Washington DC: 2003. 1001834

Comparing Energy Storage Technologies

As mentioned above, it is difficult to quantitatively compare different energy storage technologies on an apples-to-apples basis. Every application is different, and technologies that are appropriate for one application may not be fit for another. Even when applications are the same, qualitative differences between sites can make a big difference. For example, CAES may be very cost effective in an area where existing salt caverns provide a place for air storage, but may not be so attractive if caverns must be built.

The EPRI-DOE Handbook of Energy Storage[24] developed a method by which the approximate *benefits* of entire energy storage *systems* could be calculated in relation to their costs. These systems included all power electronics and balance-of-plant equipment required to perform in specific applications in transmission and distribution. Costs were calculated on a lifecycle basis, and included operations and maintenance (O&M) costs, hardware replacement costs, and disposal costs.

For purposes of illustration, we present here a less rigorous but simpler comparison of systems using initial costs alone, in three different applications relevant to wind power generation. This comparison is not a true apples-to-apples comparison, because it does not include life cycle costs such as replacement. Instead, we have calculated the approximate life of each technology in each application.

Table 3-2 shows figures for several energy storage technologies in a long-duration discharge application. The duty cycle for this application is a discharge of 10 MW for 8 hours, occurring 250 times a year.

[24] *EPRI-DOE Handbook of Energy Storage for Transmission and Distribution Applications*, EPRI, Palo Alto, CA, and the U.S. Department of Energy, Washington DC: 2003. 1001834

Table 3-2
Cost Comparison for Energy Storage for Long Durations

Energy Storage for Wind Applications: 10 MW plant with 8 hours of storage, used 250 times a year						
	Expected Cycle Life (cycles)	Expected Service Life[1] (years)	AC Round-Trip Efficiency	Initial Capital Cost for a 10 MW / 80 MWh Installation[2]	Initial Capital Cost per kW ($/kW)	Initial Capital Cost per kWh ($/kWh)
Pumped Hydro	N/A	>25 years	80-85%	$9.0 M[3]	$900	$110
CAES	N/A	>25 years	>100%[4]	$8.2 M[3]	$820	$100
Batteries						
Lead-Acid Batteries[5]	1,250	5	50-65%	$35 M	$3,500	$450
Nickel-Cadmium Batteries	3,500	14	45-60%	$98 M	$9,800	$1,225
Sodium-Sulfur Batteries	4,500	15	65-75%	$23 M	$2,300	$300
Vanadium Redox Batteries	3,500	10	65-80%	$26 M	$2,600	$325
Zinc-Bromine Batteries	2,000	6	65-80%	$40 M	$4,000	$500
Hydrogen Storage[6]	500	2	20-45%	> $100 M	> $10,000	> $1,000
SMES	> 100,000	20	90%	> $100 M	> $100,000	> $100,000
Flywheels	> 100,000	20	90%	> $100 M	> $100,000	> $100,000
Ultracapacitors	> 100,000	20	90%	> $100 M	> $100,000	> $100,000

[1] Service life calculation is based on operating conditions and cycle life, and does not include refurbishment

[2] Costs include initial installed cost for battery, power conditioning, and balance of plant, but not O&M or life-cycle costs

[3] Costs for small pumped hydro and CAES systems are extrapolated from larger systems (hundreds of MW). These systems are unlikely to be cost effective at low power levels.

[4] Because most CAES systems have a natural gas input, efficiency can be greater than unity

[5] Assumes deep-cycle lead-acid batteries

[6] Hydrogen storage figures describe state of present art; future performance may be significantly better

This table raises several points:

1. Pumped hydro and CAES systems are far cheaper than other technologies on both $/kW and $/kWh bases. This is due in large part to their larger scale and use of well-established technology. Note that neither of these technologies is normally produced at this small a power level.
2. Sodium- sulfur batteries and vanadium redox batteries look the most promising of the remaining technologies because of their low life and relatively long life. In fact, plants built with either technology can extend life still further through refurbishment of the cell stacks, a procedure much cheaper than buying a new plant.
3. Lead-acid batteries, commonly considered the default energy storage option because of its familiarity, are both more expensive and shorter-lived than alternatives.

Table 3-3 shows figures for the same energy storage technologies in a much shorter duration discharge application, for which the duty cycle is a discharge of 10 MW for 15 minutes following a triangular ramp-up and ramp-down profile. That is, the device discharges at a gradually increasing power level, reaching 10 MW in 7.5 minutes, followed by a ramp down to zero. This matches the duty cycle required for frequency regulation and ramping applications. This discharge is expected to occur 1,000 times a year (between two and three times a day).

Note that the results for a 15 minute discharge are considerably different than for longer discharges. Conventional battery technologies become considerably cheaper, particularly nickel-cadmium. Nickel-cadmium can compete well with lead-acid at this power level because it has substantially better power density than lead-acid, and therefore requires fewer batteries to do the same job. Sodium-sulfur batteries still look very attractive, especially since they can be expected to last at least twice as long as lead-acid or nickel-cadmium.

Other long-duration storage devices look less attractive in this application. For pumped hydro and CAES, it is because these technologies do not scale well, at least as the technology is used today. It is conceivable that a different approach based on these technologies could produce more cost-effective products. Similarly, VRB and zinc-bromine batteries are somewhat less cost-effective, not because of inherent weaknesses in the technology, but because present-day products are geared more towards bulk energy storage.

Finally, note that short-duration products are still not cost-effective at this rate. In the case of SMES and flywheels, this is because most modern products are based on delivering power quickly rather than storing energy. Both technologies can conceivably do better; in particular, flywheels designed for frequency regulation operations may be very cost-effective in this application.

Table 3-3
Cost Comparison for Energy Storage for Short Durations

Energy Storage for Wind Applications: 10 MW plant with 15 minutes of storage, used 1000 times a year						
	Expected Cycle Life (cycles)	Expected Service Life[1] (years)	AC Round-Trip Efficiency	Initial Capital Cost for a 10 MW / 2.5 MWh Installation[2]	Initial Capital Cost per kW ($/kW)	Initial Capital Cost per kWh ($/kWh)
Pumped Hydro	N/A	>25 years	80-85%	$6 M[3]	$600	$2,400
CAES	N/A	>25 years	>100%[4]	$5.2 M[3]	$520	$2,080
Batteries						
Lead-Acid Batteries	7,500	5	30-50%	$5.5 M	$550	$2,200
Nickel-Cadmium Batteries	7,500	7	30-50%	$5.7 M	$570	$2,280
Sodium-Sulfur Batteries	> 10,000	15	60-70%	$6.5 M	$650	$2,600
Vanadium Redox Batteries	> 10,000	10	65-80%	$18 M	$1,800	$7,200
Zinc-Bromine Batteries	10,000	10	65-80%	$8.3 M	$830	$3,320
Hydrogen Storage[5]	500	< 1	20-45%	> $100 M	> $10,000	> $100,000
SMES	> 100,000	20	90%	> $100 M	> $100,000	> $100,000
Flywheels[6]	> 100,000	20	90%	> $100 M	> $100,000	> $100,000
Ultracapacitors	> 100,000	20	90%	> $100 M	> $10,000	> $100,000

[1] Service life calculation is based on operating conditions and cycle life, and does not include refurbishment

[2] Costs include initial installed cost for battery, power conditioning, and balance of plant, but not O&M or life-cycle costs

[3] Costs for small pumped hydro and CAES systems are extrapolated from larger systems (hundreds of MW). These systems are unlikely to be cost effective at low power levels.

[4] Because most CAES systems have a natural gas input, efficiency can be greater than unity

[5] Hydrogen storage figures describe state of present art; future performance may be significantly better

[6] Describes commercially-available power flywheels; energy flywheels in development may demonstrate better cost and performance in this application

Table 3-4 shows figures for the same energy storage technologies in a very short duration discharge application. The duty cycle is a discharge of 10 MW for 30 seconds, occurring 10,000 times a year (roughly 27 times a day.)

Note that the costs for many systems do not change between the15 minute and the 30 second applications. This is because these technologies tend to be power-limited in short-duration applications; that is, their rating must be determined by their power capability rather than their energy capacity.

For a full analysis of energy storage costs and benefits on a life-cycle basis, as well as a full comparison of technologies, it is recommended that the reader consult the EPRI-DOE Handbook of Energy Storage, as well as the special supplement describing energy storage applications to wind generation[25].

[25] *EPRI-DOE Handbook Supplement of Energy Storage for Grid-Connected Wind Generation Applications*, EPRI, Palo Alto, CA, and the U.S. Department of Energy, Washington DC: 2004. 1008703.

Table 3-4
Cost Comparison for Energy for Very Short Durations

Energy Storage for Wind Applications: 10 MW plant with 30 seconds of storage, used 10000 times a year						
	Expected Cycle Life (cycles)	Expected Service Life[1] (years)	AC Round-Trip Efficiency	Initial Capital Cost for a 10 MW / 2.5 MWh Installation[2]	Initial Capital Cost per kW ($/kW)	Initial Capital Cost per kWh ($/kWh)
Pumped Hydro	N/A	>25 years	80-85%	$6 M[3]	$600	$72,000
CAES	N/A	>25 years	>100%[4]	$5.2 M[3]	$520	$62,400
Batteries						
Lead-Acid Batteries	> 10000	1	30-50%	$5.5 M	$550	$66,000
Nickel-Cadmium Batteries	> 100,000	7	30-50%	$5.7 M	$570	$68,400
Sodium-Sulfur Batteries	> 200,000	15	60-70%	$6.5 M	$650	$78,000
Vanadium Redox Batteries	> 200,000	10	65-80%	$18 M	$1,800	> $100,000
Zinc-Bromine Batteries	> 200,000	10	65-80%	$8.3 M	$830	$99,600
Hydrogen Storage[5]	> 1000	< 1	20-45%	> $100 M	> $10,000	> $100,000
SMES	> 200,000	20	90%	$62 M	$6,200	> $100,000
Flywheels[6]	> 200,000	20	90%	$12 M	$1,160	$139,200
Ultracapacitors	100,000	10	90%	$6.7 M	$670	$80,400

[1] Service life calculation is based on operating conditions and cycle life, and does not include refurbishment

[2] Costs include initial installed cost for battery, power conditioning, and balance of plant, but not O&M or life-cycle costs

[3] Costs for small pumped hydro and CAES systems are extrapolated from larger systems (hundreds of MW). These systems are unlikely to be cost effective at low power levels.

[4] Because most CAES systems have a natural gas input, efficiency can be greater than unity

[5] Hydrogen storage figures describe state of present art; future performance may be significantly better

[6] Describes commercially-available power flywheels

4

EFFORTS TO DATE, FAVORABLE SCENARIOS, AND OBSERVED BEST PRACTICES FOR INTEGRATING ENERGY STORAGE WITH WIND ENERGY

Three questions have dominated the field of integrating energy storage with wind power generation to date:

1. Does energy storage bring value to grid-connected wind generation projects?
2. When does the value brought by energy storage outweigh the costs?
3. How can energy storage be best integrated with wind generation?

The first question has been answered to the satisfaction of most researchers: a large number of studies and demonstration projects have shown that, in most cases, energy storage does bring value to grid-connected wind generation plant, by storing energy that would otherwise be curtailed, firming up wind generation, and providing ancillary benefits such as regulation and voltage support.

The more vital question is whether these benefits outweigh the considerable costs associated with energy storage. Energy storage technologies are not cheap, and it is difficult to justify them even when multiple benefit streams are taken into account. The case for energy storage will vary a great deal with the particular energy storage technology, the location of the wind generation plant, the wind availability profile, the characteristics of the power system, the local market and regulatory structure, and political considerations.

As for the third question, the science of integrating energy storage with wind generation is still very young. Most projects in this field of study have been demonstration projects or paper studies, and because every situation is unique, it is difficult to derive a set of "best practices" that covers all cases. Nonetheless, we can approach the situation systematically to see how to maximize the benefits of energy storage while minimizing the costs, with the hopes that future developments will enable more fidelity in design and operations.

Combining Energy Storage With Wind Power Generation: Efforts to Date

Several projects have been initiated to examine the integration of energy storage with wind, although only a few have led to the actual construction of hardware. The first five projects here describe projects which have led to the installation of energy storage with wind turbines; the remaining projects have so far been examined only in paper studies.

San Gorgonio, California

In the U.S. in 1992 and 1993, a 2.88 MW / 17.28 MWh lead-acid battery facility was operated integrally with wind generation by a private wind developer in the San Gorgonio area of California. The project operated successfully for two annual peak seasons. The purpose was to meet firm capacity contract obligations prior to the repowering of an early wind farm. The batteries were surplus submarine batteries packaged in 360 kW modules with six hour storage capacity[26].

Institute of Applied Energy (Japan)

The Institute of Applied Energy (IAE) is a research foundation based in Tokyo, Japan, 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) to conduct a field study for the stabilization of output of wind turbines with storage batteries[27].

The IAE project was intended to investigate the use of energy storage to mitigate power fluctuations as a result of wind gusts. As such, the use of storage batteries was investigated on a relatively small scale. For each of the three projects, one battery was connected to one wind turbine in an effort to reduce the fluctuations related to the turbine. The projects were intended to investigate the economics of using energy storage for this application, as well as the technical advantages and disadvantages. Three field demonstrations were implemented: One conducted with a NAS battery, another with a vanadium redox battery, and the third with a valve-regulated lead-acid (VRLA) battery.

The NAS battery application followed early research by Tokyo Electric Power Company (TEPCO) on using NAS batteries to mitigate power fluctuations from wind turbines. An early field test, using a 50 kW NAS battery connected to a 300 kW wind turbine, was begun in December 1995 at the TEPCO New Energy Park. This demonstration showed the validity of the project, and TEPCO proceeded with the larger NEDO project at the Hachijojima Wind Power Station, located on the island of Hachijojima about 300 km south of Tokyo. Here, TEPCO installed a 400 kW NAS battery, capable of providing power for 7 hours, to stabilize the output of a single 500 kW wind turbine. The installation allowed nearly complete stabilization of the wind turbine output with respect to fluctuations, as well as allowing time shifting operations[28].

The vanadium redox battery application was sited at the Horikappu Power Plant operated by Hokkaido Electric Power and located near Tomamae in Hokkaido, Japan. The vanadium redox battery, supplied by Sumitomo Electric Industries, is used to stabilize the output of a 250 kW wind turbine. The battery is sized to provide 170 kW for six hours. The battery entered service in March 2001, and provided both fluctuation suppression and time shifting capability[29].

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[26] Communications with Hal Romanovitz with Oak Creek Energy Systems, December 2004. Also see Chapter 12 of Wind Power in Power Systems, ed. T. Ackermann, John Wiley & Sons. Publication expected March 2005.
[27] NEDO press release, September 2000
[28] IERE website, http://www-iere.dcc.co.jp/Current_Topics/TEPCOjp/NAS/03appl/frame-renew.html
[29] Sumitomo Electric Industries website, http://www.sei.co.jp/redox/youto/furyoku.html

The VRLA project was installed at Tohoku EPC Cape Tappi Number 7 wind turbine. The VRLA battery was sized to provide 200 kW for four hours, and was paired with a single 300 kW wind turbine to provide fluctuation suppression as well as time shifting services. The test of the VRLA system began in April 2001 and ran for eight months[30].

In each of these three cases, the original intent was the stabilization of wind turbine output with respect to short-term fluctuations. The study found that medium- and long-term variability (on a time frame of minutes or hours) were significantly larger problems than short-term fluctuations (less than one minute). This was because short-term fluctuations tended to vanish when aggregated over large numbers of wind turbines, while longer-term variability did not. The study further found that each of the three technologies investigated had a "sweet spot" with respect to cost, depending on the duration of discharge. Lead-acid batteries were cheapest for durations less than two hours, VRB for durations between four and six hours, and NAS for durations longer than eight hours.

Despite these findings, the cost factor loomed large over the practicality of this application. It was calculated that the effective cost per kW for a wind generation project incorporating energy storage would be 1.4 to 1.8 times the cost per kW for the wind generation system alone. The authors concluded that energy storage costs must come down significantly for energy storage to be economically viable[31].

Dogo Island (Japan)

In August 2003, Fuji Electric, a Japanese electric equipment and system vendor, installed a 200 kW Urenco flywheel at an 1800 kW wind farm on Dogo Island in Japan. The wind farm is composed of three 600-kW DeWind 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[32]. This demonstration showed that flywheels could be used to reduce short-term variability for small wind farms.

Denham Wind/Diesel Project (Australia)

Powercorp, an Austalian integrator of wind power and diesel generator systems, has developed a control system called the Intelligent Power System (IPS), which 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 as 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 at 230 kW. These turbines were tied with two 200-kW

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[30] NEDO, "Investigation into the Possible Use of Storage Batteries for Stabilization of Wind Power Generation," February 2002.
[31] Ibid.
[32] Urenco Power Technologies, "Fuji Wind Diesel Power Case Study," http://www.uptenergy.com/eng/applications/renewablepower/casestudy/fuji.htm

flywheels installed in parallel to provide 400 kW for up to 90 seconds. The stabilization has allowed the diesel engines to run more efficiently, leading to significant savings in diesel fuel[33].

King Island (Tasmania, Australia)

King Island is a small island to the northwest of the main island of Tasmania. The island has a population of about 1,500 and is largely rural, with a number of small towns on the coast. Most land is agricultural, and there are no large industries. As such, the island has a small grid with a maximum demand of about three to 3.5 MW during the day, and about one MW at night. Traditionally, power has been provided by diesel generators. The relative expense of bringing diesel to the island encouraged HydroTasmania, the local utility, to explore alternative options, including wind generation.

In 1998, HydroTasmania established the Huxley Wind Farm near the town of Currie, in close proximity to the island's main diesel power station. The three 250 kW Nordex wind turbines installed at Huxley provided about 18% of the island's power requirements, with the balance serviced by a diesel power station. HydroTasmania found that the three wind turbines caused considerable fluctuations on the King Island grid, and explored various ways of mitigating these fluctuations before 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 with two 850 kW Vestas wind turbines and a 200 kW vanadium redox flow battery supplied by Pinnacle VRB, an Australian developer of vanadium redox systems.

The flow battery consists of six stacks produced by Sumitomo Electric, with the capability of delivering 200 kW for four hours (for load shifting) and a peak power capability of 400 kW for 10 seconds (for fluctuation mitigation). The battery was originally intended for both fluctuation stabilization and time shifting applications. After the installation of the Vestas turbines, it was found that fluctuation problems had been significantly reduced by the mitigation technology incorporated into the turbines themselves. As a result, it is now expected that the battery will be used primarily for time shifting.

Figure 4-1
VRB Facility on King Island, Tasmania *(Courtesy HydroTasmania and Pinnacle VRB)*

[33] Powercorp website, www.pcorp.com.au.

Grid voltage and frequency are managed by a sophisticated control system, which delivers power from a combination of the wind turbines, the battery, and diesel generators. Grid voltage and frequency are usually controlled through the diesel generators, rather than through the battery. This is because the battery is too small to adequately compensate for the long-duration intermittency on the wind turbines. The battery can, however, reduce the rate of change produced by short-term intermittency on the wind turbines, reducing the rate at which they affect the voltage and frequency on the grid.

As of this writing, the King Island energy storage system is undergoing final testing and verification in preparation for full-time operation scheduled to begin in mid-2005[34].

J-Power (Japan)

The earlier field demonstrations funded by NEDO gave the agency enough confidence to try larger energy storage installations designed to mitigate fluctuations and intermittency for entire wind farms, rather than for individual wind turbines. In 2003, NEDO funded a consortium including Hokkaido Electric Power, J-Power (a Japanese generation utility), and Sumitomo Electric Industries to install a vanadium redox battery at the Tomamae Wind Villa wind farm in Hokkaido.

The Tomamae facility consists of 19 wind turbines (14 rated at 1650 kW, 5 at 1500 kW) with a total output power of 30,600 kW. Simulations by Hokkaido Electric Power and others indicated that a battery capacity of at least 20% of the facility is required to provide useful stabilization. Accordingly, the vanadium redox battery was sized to provide 6000 kW for 20 minutes or 4000 kW for 1.5 hours, with an inverter sized at 6000 kVA. The vanadium redox battery was judged the most suitable technology for the installation because of its high power output and independence between power and energy input.

The Wind Villa VRB battery is scheduled for commissioning by early 2005, and will operate until 2008. When built, it will be the first commercial-scale demonstration of energy storage for grid-connected wind power enhancement[35,36].

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, resulting in losses to wind developers. Further, the system operator, Electric Reliability Council of Texas (ERCOT), was obligated to pay wind developers for lost energy production.

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

[34] Conversation with Andrew Hickman, HydroTasmania, November 2004.
[35] J-Power Press Release, September 3, 2003.
[36] Conversation with Rick Abe, J-Power, Fall 2004.

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[37]. 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 several megawatts of power for several hours. 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 compression power and 270 MW generation capacity with an energy storage capacity of 10,000 MWh. The capital 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 an annual carrying cost of about $30 million per year, covering interest and principal on debt as well as return to equity investors under an appropriate financing structure. Other included costs are recurring fixed expenses such as upkeep, property taxes, insurance, business management, and utilities. Fuel costs were estimated at $5/MMBtu. Variable operations and maintenance costs were estimated to range between $3 and $5 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 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 addressed only the transmission benefits of energy storage and did not address 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 compares to the cost of a CAES plant[38]. The Ridge Energy model identified several other value streams for a CAES plant, and considered 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

[37] Study of Electric Transmission in Conjunction with Energy Storage Technology, led by Lower Colorado River Authority, with support from Ridge Energy Storage & Grid Services, RnR Engineering, and Walter J. Reid Consulting, Austin, Texas, August 21, 2003.
[38] N. Desai and D. Pemberton, "Economic Value of Compressed Air Energy Storage in Conjunction with Large-Scale Wind in McCamey," EESAT 2003, San Francisco, CA October 27-29, 2003.

CAES systems, which show enormous value over time. The value easily exceeds the levelized annual cost, as shown in Figure 4-2.

The benefits include: Recovered energy, REC (renewable energy credits) and PTC (production tax credits) come about as a result of curtailment reduction. These benefits decrease in 2009 and 2013 as new transmission lines become available. CAES uplift, net shaping, and capacity value persist, however. Note that the benefits described here do not include ancillary or arbitrage services, which might add even more value to the project.

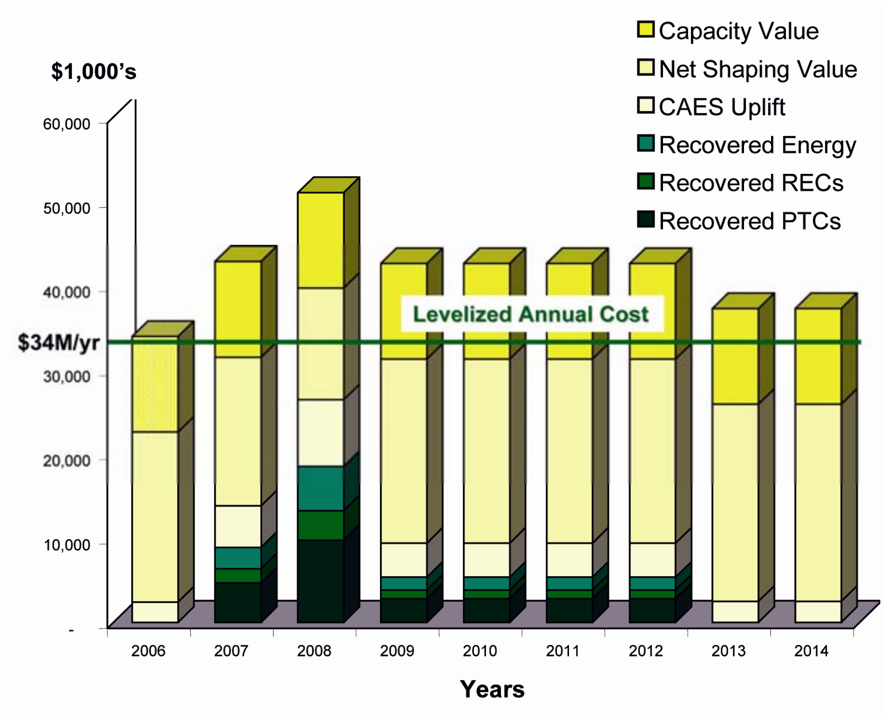

Figure 4-2
Changes in CAES Value Over Time[39]

The West Texas CAES project is still under study. In the meantime, alternative solutions to the transmission congestion issue have been initiated. Transmission upgrades have been approved and are proceeding. EPRI is also evaluating improved forecasting tools that may help make wind contracts less risky.

The full details of the West Texas case are discussed in greater detail in an earlier EPRI report[40].

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[39] Adapted from N. Desai and D. Pemberton, "Economic Value of Compressed Air Energy Storage in Conjunction with Large-Scale Wind in McCamey," EESAT 2003, San Francisco, CA October 27-29, 2003.

[40] Wind Power Integration Technology Assessment and Case Studies, EPRI, Palo Alto, CA: 2004. 1004806

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 Fort Dodge in north central Iowa as the possible site of a CAES plant. 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 of wind generation paired with a 100 to 200 MW CAES power plant. The CAES plant could be charged from either wind or 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. The plant is scheduled to begin operation by 2009[41,42].

Hawaii Big Island

In July 2004, Hawaiian Electric Company (HECO) received a patent for an "electronic shock absorber," a device that would use ultracapacitors to dampen frequency fluctuations caused by short duration variability in the 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, and a minimum load of 80 MW. The island has a total installed power generation capacity of about 255 MW, including an installed wind capacity of about nine MW. 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 the power transmission line. The system is designed to level the output of wind turbines by injecting power form the ultracapacitor system when the wind flags and recharging the ultracapacitor 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 prototype is expected to be tested in 2005[43].

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[41] J. Haahr, "The Iowa Stored Energy Plant," ESA 2004, Columbus OH, May 19-20, 2004.
[42] Communication with Kent Host of ISEP, November 2004
[43] HECO Press Release, July 19, 2004

In parallel with the HECO process, Hawaiian Electric Light Company, 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 wind and other renewable power generation 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, have made it necessary to upgrade the island's transmission network. While part of this upgrade will be accomplished through traditional transmission investment, energy storage is also being examined as an option.

In this application, it is expected that an energy storage plant would be of significant capacity for both power and energy. HELCO and SENTECH have identified the need for one 20-MW/30-MWh energy storage system, or two 10-MW/15-MWh energy storage systems at different locations[44].

Foote Creek Rim (Wyoming)

In 2004, a study was begun for the potential use of vanadium redox technology based on wind energy production from the Foote Creek Rim wind 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. The site suffers from severe transmission constraints at certain times, however, forcing wind curtailment. The energy storage 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 analysis 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 ratings, the relatively quick response time, the high efficiency, and the positive experience with VRB technology at the Moab, Utah facility[45].

Maximizing the Value of Energy Storage for Wind Generation Support

At present, the biggest obstacle to the use of energy storage for supporting grid-connected wind generation is the high cost of energy storage technologies. To offset this cost, an energy storage plant must provide as many benefits as possible. The cost/benefit equation is sensitive to a number of considerations, including:

- Geography of the site
- The wind profile at the site
- Characteristics of the power system in the vicinity of the site
- Local market and regulatory structure
- Environmental considerations

[44] HELCO, Inc. and Sentech, "HELCO Operational Issues – Bulk Energy Storage," Draft in November 2004.
[45] Communication with Mindi Farber-DeAnda, SAIC, November 2004.

We will now consider these issues one at a time.

Geography

The geography around a potential site has impacts on several considerations for both wind generation and energy storage. The geography often dictates the size and shape of the wind farm, how far apart the individual wind turbines are, and how wind profiles will vary across the farm. In addition, geography may shape the nature of the local electrical network: a grid on a remote island, for example, is unlikely to be connected to a larger grid for support. A wind farm in a remote location may suffer from insufficient transmission, especially at peak times.

Geography also affects the types of energy storage facilities that are available for a particular site. Pumped hydro is most feasible where there is both a large quantity of available water and the potential for a significant height difference between upper and lower reservoirs. CAES systems require large underground storage caverns or aquifers of particular geometry and composition. If such geographical features are not available, the developer may have to settle for using other technologies such as NAS or VRB, which may make energy storage less attractive.

Wind Profile

Energy storage applications depend in part on the wind profile at a generation site. Time shifting applications make sense when the wind availability is not congruent with the power demand profile. Forecast hedging applications make sense if the wind forecasts are not reliable. The presence of short-term variability across the wind farm may make fluctuation suppression desirable.

Sizing of an energy storage product can also be determined from the wind profile, along with market data. For example, if peak wind availability occurs six hours before the peak demand, three to four hours of storage may be sufficient to improve the economics of the wind farm. If peak wind availability occurs 12 hours before the peak demand, however, six to eight hours of storage may be more appropriate.

The time scale for wind variability is also important to an energy storage decision. If significant variability is seen on a short time-scale (20 to 60 seconds) then energy storage might make sense as a way of reducing this variability. In general, the larger the wind farm, the more likely that the short-term effects of the wind profile will average out across the entire farm. For this reason, short-term fluctuations are not as visible for large wind farms, especially those using modern drive systems which minimize the effects of gusts and lulls[46].

[46] For more information, see *Engineering and Economic Evaluation of Wind System Design Innovations for Smoothing Power Fluctuations*, EPRI, Palo Alto, CA: 2005. 1008389

Power System Characteristics

The characteristics of the local power system are the other major technical factor in energy storage applications. There are two major considerations that must be taken into account: energy dispatch and grid regulation.

First, the way that energy is delivered through the local power system is critical, particularly the change in the power load over a typical day. Time-of-day load profiles and power load flow analyses can be used to determine whether there are opportunities for bulk energy storage applications such as curtailment reduction, time shifting, and forecast hedging.

Secondly, it is important to note the way in which generators regulate frequency in the face of changing loads. This will partly depend on the mix of generation in a geographical area as well as the size of the load. Some types of generation, such as nuclear, do not follow changes in load well. As a result, faster responding generation such as hydroelectric or combustion turbines are used to quickly ramp up and down to follow changes in load.

The introduction of wind power generation into the power system complicates matters somewhat. Because it is not dispatchable, it can not be relied on to follow the time-of-day profile; it may deliver power when it is not needed (forcing curtailment) or not deliver power when it is required (forcing the operator to provide power from other units or shed customers). Nor can the wind be used as a regulation unit, since it cannot be fully controlled for ramping. In fact, variability in the wind may cause the amount of power generated to move in exactly the opposite direction as necessary for regulation, meaning that the wind plant actually makes the problem worse.

Figure 4-3 shows an example of this type of system. The graph shows a projected case for power delivery from various types of generation on the Big Island of Hawaii, managed by Hawaii Electric Light Company (HELCO). It is assumed that all base-load units (largely geothermal) and hydroelectric units (mostly run-of-the-river) are fully utilized. Regulating generation is available to follow the daily profile, but must be set to a minimum generation figure to stand prepared. The remaining load is picked up by wind generation. Note that in the morning, the wind generation is not used, leading to curtailment; in the afternoon, the peak load is barely met by all units running at full power, so that if wind power falls off, load must be shed.

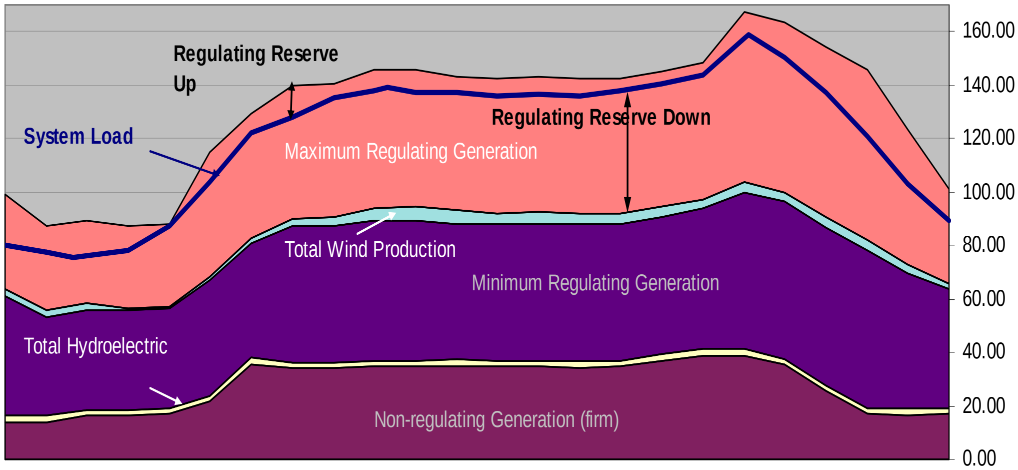

Figure 4-3
HELCO Load Curve and Generator Dispatch Measured on a Typical Spring Day

An energy storage system would bring several potential benefits to this system:

1. Curtailment mitigation: Energy storage could be used to store wind energy generated in the early morning, which would otherwise be wasted.
2. Hedging: Energy storage could be used to cover shortfalls in the afternoon, if wind generation is not available.
3. Regulation: Energy storage can be used to provide ramping during load shifting, and possibly provide power for entire peak periods. This would reduce the necessity of inefficient ramping units and expensive peak power, and allow assets to be more fully utilized.

Clearly, these benefits would be smaller if the wind generation did not make up such a large part of the generation mix in this particular case. Energy storage makes the most sense when a very large amount of wind generation is present (as in the West Texas case described above) or when the grid itself is relatively small, so that even a small amount of wind has a large impact on the grid (as in the HELCO case).

Rather than being paired specifically to wind power generation, the regulation benefits of energy storage can be considered ancillary benefits to the grid itself. As such, these benefits depend heavily on the market and regulatory structure in the area, as described in the next section.

Local Market and Regulatory Structure

The local market and regulatory structure is possibly the most important consideration in determining if and how energy storage can be used effectively for a particular site. There are vast differences between the ways that both wind power generation and energy storage are treated in markets in various parts of the United States, let alone in other countries. In practice, this means that the value of both wind and energy storage may be very large in one market and very small in another, even if the technical considerations for the two are identical.

The varying value applies particularly to the ancillary benefits of energy storage. These benefits include supplying spinning reserve, frequency regulation control, voltage support, and black start services. If the value of ancillary benefits is leveraged properly, the economic case for energy storage may become much more attractive.

This case is dramatically illustrated in a study conducted by the Tennessee Valley Authority (TVA)[47]. The study examined the value of reserves, regulation services, and energy arbitrage for hypothetical energy storage systems in three different ISO areas. The value of the different components varied a great deal between the three cases, as represented in Figure 4-4. In two markets, regulation services provide the vast majority of benefits; in the third, the benefits were more somewhat more evenly distributed. (The fourth case shown here is a special version of the third.)

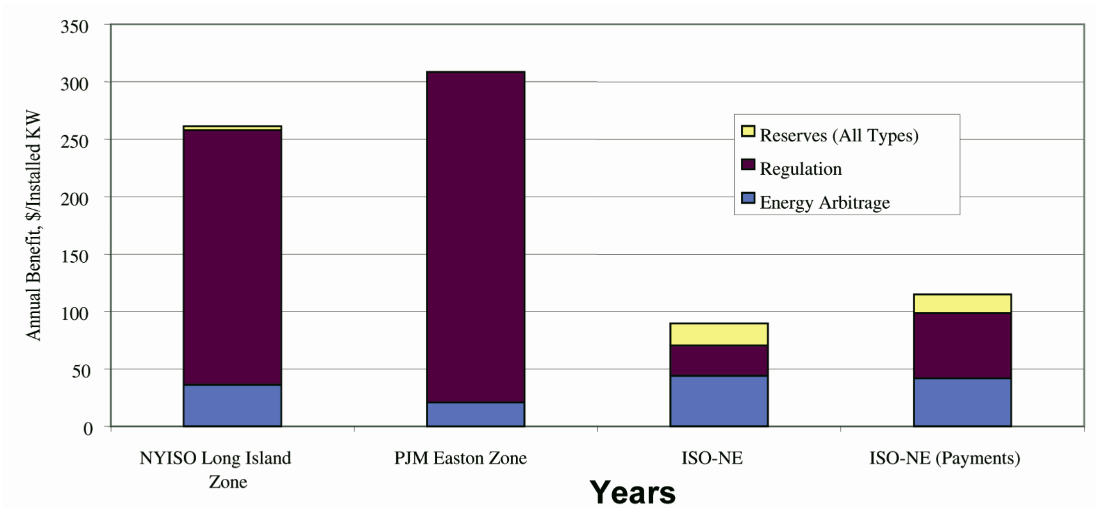

Figure 4-4
Storage Operating Benefits in Ancillary Services Markets (Taylor, et al)[48]

The graph demonstrates the necessity of investigating the total benefits derived from energy storage, as well as the breakdown of those benefits, in the light of market and regulatory conditions as well as on a technical basis.

Environmental Considerations

Naturally, political considerations also play an important role in deriving the value of an energy storage system in support of wind power generation. The most important such consideration is environmental regulation and sentiment, especially for large-scale plants such as pumped hydro and CAES. Such plants can have serious environmental consequences, and may run into local opposition. Even otherwise, permitting for such plants can take years if not decades. Other energy storage technologies also have their share of environmental concerns; many technologies incorporate toxic or flammable materials and require special permitting. There have been several cases in which an energy storage plant makes technical and economic sense but is politically impossible for environmental reasons.

[47] R. Taylor, J. Hoagland, D. Bradshaw, *Energy Storage for Ancillary Services*, EESAT 2002, San Francisco, California, April 15-17, 2002.
[48] Ibid.

Scenarios Favoring the Use of Energy Storage

Based on the previous discussion, we can describe four broad cases in which energy storage is likely to make both technical and economic sense:

1. **Locations on islands or weak power networks:** Small power networks are particularly susceptible to wind integration issues. On larger grids, wind power makes up a small part of the total power moving through the network, and the effects of these issues are small. On smaller grids, however, the effects of intermittency, ramping, fluctuating output, and limited reactive power can diminish the capability of the grid. At present, the problem is often solved with fast-acting generators which can quickly ramp up or down to match load. This solution is often expensive in island and remote locations, however, because of the costs of transporting fuel.
2. **Remote locations with constrained transmission:** Wind generation locations without sufficient transmission to transport the power they produce will usually benefit from energy storage systems. Because such systems also provide time-shifting and forecast hedging benefits, the benefits of the energy storage persist even if the transmission system is subsequently upgraded.
3. **Areas with special market structures:** Markets for energy arbitrage or for ancillary services such as frequency regulation and spinning reserve may make energy storage a compelling case for T&D utilities in some areas, even if the benefits to wind generators are not particularly large.'
4. **Locations with low-cost energy storage:** Since energy storage always holds benefits when integrated with wind energy, it is advantageous to use energy storage if it is already available at low cost. For example, existing pumped storage or CAES units may deliver more benefits when used to store wind energy for time shifting, in addition to their original purpose.

Table 4-1 summarizes each of theses cases.

Table 4-1
Scenarios Favoring the Use of Energy Storage

Scenario	Wind Integration Issues	Potential Energy Storage Applications
Locations with Low-Cost Energy Storage	Intermittency, ramping burdens	Curtailment reduction, time-shifting, forecast hedging, frequency regulation
Island or Weak Networks	Intermittency, ramping burdens, fluctuating output, limited reactive power	Curtailment reduction, time-shifting, forecast hedging, frequency regulation, fluctuation suppression
Constrained Transmission	Intermittency, ramping burdens, remote locations	Curtailment reduction, time shifting, forecast hedging, frequency regulation
Areas with Special Market Structures	Intermittency, ramping burdens, fluctuating output, limited reactive power, remote locations	Curtailment reduction, time shifting, forecast hedging, frequency regulation, flluctuation suppression

Best Practices for the Use of Energy Storage Integrated With Wind Generation

In modern business language, "best practices" describe those operational procedures which, through intelligent design and fine honing through long experience, have been found to result in the most effective and efficient function of a business. In this context, "effective" means that a business succeeds in meeting the expectations of its customers, owners, and operators, and "efficient" means that it does so while using as few resources as possible.

The idea of "best practices" is usually applied to mature business operations which are well-developed, if not always well-understood. This description certainly does not fit the integration of energy storage with wind generation, a technique which is still relatively immature. There has not been sufficient time to judge whether the existing integration approaches are effective and little experience to suggest how they could be made more efficient.

It is possible, however, to define best practices for studying the use of energy storage to support wind power generation. Ideally, such study should take place when the wind generation facility is first proposed, so that the value of the overall wind generation system can be assessed.

On the basis of past efforts, it is possible to define a six-step process for studying the integration of energy storage with wind generation:

1. Wind and power system data collection
2. Application selection
3. Energy storage technology decisions
4. Control algorithm development
5. Analysis and simulation of performance, operation, and economics
6. Cost and benefit analysis

We will now examine each of these in detail.

Wind and Power System Data Collection

A good understanding of the impact of a wind generation project on the utility grid is required before such a project is constructed. An incorrect or incomplete understanding can lead to problems such as voltage disturbances and unbalance, poor utilization, and wasted energy due to curtailment. This is still true when energy storage is linked to wind generation, since the value brought by storage depends heavily on how it is sized and integrated into the system. Since any analysis requires accurate and appropriate data as an input, the proper collection of wind data and power system data is the first step to any study of energy storage integrated with wind generation.

Wind data used in these types of analyses generally consist of wind data across at least one year, taken at one-hour or 15-minute intervals. Where available, wind forecasts can be used to develop better ideas of how wind availability translates into power generation. A number of forecasting tools have been developed for this purpose, as described in detail in the previous EPRI report on wind power integration[49].

Power system data should include, at a minimum, time-of-day rate structures for the area where energy storage is being considered. This allows calculation of time shifting benefits and forecast hedging benefits, and a partial calculation of potential transmission curtailment reduction benefits, without involving all of the technical considerations of a grid modeling exercise. Nonetheless, it is highly recommended that a power flow model for the area be used to fully model the effects of the energy storage and wind generation on the surrounding system.

[49] Wind Power Integration Technology Assessment and Case Studies, EPRI, Palo Alto, CA: 2004. 1004806

Application Selection

An initial assessment can usually be made for potential energy storage applications, or operating modes, at the site. Application selection depends on the specific integration issues encountered. For example, a wind farm generation mostly at night may require only a time shifting application, while a farm connecting to a sometimes constrained transmission line may require only a curtailment reduction application. Application selection may also depend on the market structure of the area – in an area where frequency regulation services are valuable, the ability to perform such services will be important.

Ideally, the same energy storage system will be capable of serving several applications for a site. The energy capacity of the system is an important factor in determining whether this is possible. As seen earlier, three wind generation applications – curtailment reduction, time shifting, and forecast hedging – require long-duration energy storage systems with several hours' worth of capacity. One application, frequency regulation, requires several minutes' worth of capacity. The last application, fluctuation stabilization, requires less than a minute's worth of capacity. Conceivably, energy storage systems designed for frequency regulation might also be used for fluctuation stabilization, provided the response time is fast enough. Similarly, energy storage systems designed for curtailment reduction or other long-duration applications might also provide frequency regulation, provided the system is suitably sized. As we will see, whether this can actually be done depends on the energy storage technology as well as whether applications conflict with each other.

Energy Storage Technology Decisions

The choices for energy storage technology should now be narrowed down by looking at site characteristics, potential applications, and a first glance at the business case for storage.

Of the energy storage technologies examined earlier, four seem especially suited to the long-duration energy storage systems required for wind generation applications: Pumped hydro, compressed air energy storage (CAES), sodium-sulfur (NAS), and flow batteries, particularly vanadium redox flow batteries (VRB).

Pumped hydro and CAES have demonstrated the capability to store and deliver hundreds of MW for several hours. Where feasible, these systems are preferred for energy storage because of their relative maturity and low cost in terms of amount of energy stored. Any site considered for these options, however, must be thoroughly vetted from a geological and environmental standpoint. Such a process is likely to take a long time, as it has for CAES in West Texas and Iowa. It is entirely possible that the integration issue that is to be addressed by the storage plant will be tackled through other methods in the meantime.

NAS and VRB systems have not been built to the same scale, but have demonstrated the same ability at the hundreds of kW level, with potential to operate at the MW or tens of MW level. In areas where CAES and pumped hydro are not technically feasible or cost effective, NAS and VRB may be a viable alternative. These technologies are relatively new and untested, however, and require a significant amount of patience and effort to adapt correctly.

It is also important to consider the *business* considerations of technology selection. The selected contractor must be both experienced in utility-scale energy storage and committed to the project at hand. At present, many utility-scale energy storage proposals will be first-of-a-kind projects. As a result, a strong commitment is required from both the storage technology developer and the wind developer. This level of commitment is best guaranteed when the project and application hold strategic interest for both parties.

At times, storage technology decisions have been made on the basis of political considerations rather than a real evaluation of technical benefits. Needless to say, these decisions often lead to projects with limited real value for both the generator and the technology developer. Even in cases in which strategic interest favors one technology over another, all parties have an interest in ensuring that sizing and other technical decisions are made on the basis of thorough analysis before a project is green-lighted.

A final decision technology is selected, however, to ensure that the technology is determined by the real needs of the system. This process is more effective than shoehorning a particular technology into an application.

Control Algorithm Development

Proper operation of the energy storage device requires a control strategy that allows the owner meet his goals in all operating modes. The development of a control algorithm requires that a list of priorities be set for operating modes of the system, which will lead to a set of operating parameters that will be set on the basis of certain inputs, such as conditions on the grid and the amount of wind power generation available.

The priorities for applications will depend on who is operating the energy storage. It is possible, for instance, that a wind developer would want curtailment reduction as the first priority, while a grid operator may prefer frequency regulation as a first priority.

In the early stages of the analysis, a great deal of precision in the control algorithm is unlikely and unnecessary. The main goal at this stage is to model how the energy storage system will react to inputs, for use in the power system model. The control model will undoubtedly evolve with time and deeper analysis of the entire power system.

Analysis and Simulation of Performance, Operation, and Economics

The information gathered so far can now be used to construct a simulation of performance in the particular scenario at hand. There are two types of analysis to be performed in the first run, a technical analysis and an economic analysis.

The depth and detail of the initial technical analysis will depend on the data available. Initially, simple mathematical models might be used to judge whether the situation is worth further study. Later, more complex load flow models should be used to determine the specific technical benefits deriving from an energy storage system of specific power rating, energy capacity, and location. Sizing of an energy storage system is usually performed through an iterative process, beginning with several likely sizes being tested in the system model for benefits. The analysis should take into account the basic technical parameters of the intended energy storage technology, such as response time and ramping rate, as well as the control algorithm which sets priorities for its actions.

The technical analysis should assume that the energy storage device has a reasonable duty cycle in each operating mode, as determined by the control algorithm. The analysis methodology should have sufficient fidelity to see whether applications conflict in usage – that is, whether operating an energy storage system in one mode will reduce the ability to operate it in others.

The economic analysis should next examine the value of the energy storage device operating according to the technical analysis, according to a duty cycle prescribed by the technical analysis. The economic analysis should take into account how much time the energy storage device actually spends in each mode.

Both technical and economic analyses are iterative processes. Initial analyses are used to refine the technology selection, sizing, and control algorithm design, which are used in a second analysis. Often, a third iteration is run during construction or testing to refine control strategies with real data acquired from the equipment.

Cost and Benefit Analysis

The final and most important analysis is the cost and benefit analysis, which examines whether the benefits garnered from the construction of an energy storage system outweigh the costs. Most such analyses are performed on a net present value (NPV) basis, which calculates both costs and benefits in terms of the time value of money. Like the technical and economic analyses, the cost and benefit analysis is usually an iterative process.

Costs for the energy storage plant are usually calculated on an annualized basis, including:

- Initial capital cost for the plant and all hardware (including power conditioning, balance of plant, transformers, ac connection equipment, and any other necessary equipment)
- Fixed O&M costs, which include routine monitoring and maintenance
- Variable operating costs, which include fuel costs (if applicable) and the cost of charging electricity
- Replacement costs, if required over the lifetime of the plant
- Disposal costs, if applicable at the end of the plant life
- Rent and property taxes, if applicable

Benefits are also generally calculated on an annualized basis. The analysis should include any change in benefits as the situation changes. New generation or upgraded transmission assets, for example, may change the benefits significantly. Most analyses use a worst-case scenario to calculate potential future benefits.

The EPRI-DOE Handbook of Energy Storage[50] uses a net present value (NPV) methodology to calculate the costs and benefits for generic energy storage systems sized for certain applications. This methodology compares the costs and benefits of an energy storage solution to the costs and benefits of alternative solutions in the same application. This approach allows a calculation of the value of energy storage despite the lack of specific information regarding a site. A similar calculation can be done for site-specific cases, to ensure that energy storage is in fact the most cost-effective solution to integration issues.

[50] *EPRI-DOE Handbook of Energy Storage for Transmission and Distribution* Applications, EPRI Palo Alto, California, 1001834, December 2003.

5
SUMMARY

Despite being a seemingly complementary technology, energy storage has not been widely applied to wind power generation in the field. The limited experience at present shows two major reasons for this approach:

1. Energy storage technologies are expensive, leading wind developers and utilities to other, more familiar solutions
2. In most jurisdictions, energy storage brings limited benefit to the wind developer. As a result, if energy storage plants are to be built, grid operators must be involved either as the sole operator or jointly with the wind developer.

Despite these obstacles, there are several scenarios in which energy storage seems to make sense as a solution to integration issues:

- Locations with small or weak grids can benefit from energy storage technologies to stabilize the system. This is particularly true for geographical islands, where fuel for alternative solutions can be very expensive.
- Wind farms in locations limited by transmission constraints may be forced to curtail power production when transmission is congested. This can lead to wasted energy and lost revenue. Energy storage can be used to store the energy produced during these times and deliver it later when transmission is not congested.
- Energy storage can be more valuable in locations with market structures that allow energy arbitrage or the sale of ancillary services, which can bring additional benefits to offset the cost of energy storage.
- In locations where low-cost energy storage already exists, integration of the energy storage with wind generation can bring additional benefits to both.

There is not yet enough experience to rigorously define best practices for integrating energy storage with wind for all cases. Nonetheless, the projects undertaken so far have developed extensive practices for studying the problem and recommending approaches for individual cases. With the application of these practices, it is possible that the use of energy storage will expand as wind generation becomes a more important part of the generation mix.

Export Control Restrictions

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