Using Energy Storage to Ease Integration of Wind Generation with the Power Grid[1]

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Introduction

Energy storage is often cited as a possible solution for several of the major issues associated with integrating wind generation with the existing transmission network. 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 and regulation needs and reduce concern about short-term fluctuations in wind output. Remote wind locations with constrained transmission lines can be better utilized with energy storage, which would allow scheduling of power flow when transmission capacity is available. Energy storage solutions can certainly support higher penetration of wind power into the electric grid and these storage applications will typically bring other potential value to grid operations.

Despite this potential, several issues have limited the deployment of energy storage technologies in large-scale applications. There are always application challenges for optimizing the power and energy performance for the specific storage technology and installation at hand. When a system is designed for a particular operating duty there are usually tradeoffs for using the same system for other value-added functions. Additionally, many of the technologies proposed have been commercialized only very recently and have yet to prove themselves for such operations. The most important obstacle to the use of energy storage solutions, however, is cost. The installed cost of energy storage technologies must fall significantly before they can be widely implemented for wind applications.

Nevertheless, even today, energy storage can prove cost-effective in certain situations. In addition to solving technical problems related to wind power integration, energy storage may be used to increase the capacity credit allowed to a wind power generator. It might also be used to provide ancillary services in a deregulated market. In some situations, these benefits combine to produce a compelling case for energy storage. The case for energy storage in these applications has been investigated by EPRI and the U.S. Department of Energy (DOE) in a number of recent publications. The *EPRI-DOE Handbook for Energy Storage for Transmission and Distribution Applications* (EPRI 1001834, December 2003) consolidated a framework for the analysis of energy storage technologies for utility-scale applications, building on previous work funded by DOE and others. A supplement to the Handbook, *Energy Storage for Grid-Connected Wind Generation Applications* (EPRI 1008703, December 2004) used the same framework to analyze applications related to wind generation. These reports join three other EPRI reports, *Wind Power Integration Technology Assessment and Case Studies* (EPRI 1004806, March 2004), *Wind Power Integration: Energy Storage for Firming and Shaping* (EPRI 1008388, released March 2005), and *Wind Power Integration: Smoothing Short-Term Power Fluctuations* (EPRI 1008852, released March 2005), which address the critical issues of integrating wind power with the grid and the role of energy storage in that endeavor. From this body of work, several themes have emerged that we believe describe the most likely application of energy storage to wind generation in the coming years.

Cost-effective Storage Technologies for Bulk Energy Storage Applications

Several different storage technologies have been commercialized recently, and many of them have been touted for wind power applications. While some of these technologies may hold promise for the future, at present we believe only four energy storage technologies—pumped hydro, compressed air energy storage (CAES), sodium-sulfur (Na/S) batteries, and vanadium redox flow batteries (VRB)—appear to offer positive cost-benefit analyses in long-duration energy storage applications currently considered interesting for wind-power applications.

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[2] Sandia is a multi-program laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Pumped hydro is a mature technology that is widely used in several places around the world, with over 80 GW of installed capacity around the world. Pumped hydro is extremely effective as a bulk energy storage mechanism, but must be located in areas with suitable geography. While the cost of pumped hydro systems is relatively small from a $/kW standpoint, most sites are relatively large (from several hundred to several thousand MW) and the total cost for these massive projects can be quite large. Environmental concerns can also make it difficult to site these projects. Because of these issues, most suitable pumped hydro sites that can be cost-effectively developed have already been developed, and the scope of new projects for the future is limited. Existing plants can be shifted towards use in wind applications, however, and this has been proposed in several locations.

CAES is also a relatively mature storage technology, but has been put into practice in only two locations, one in Germany and the other in Alabama. Most proposed CAES projects use underground caverns or aquifers to store compressed air. As a result, CAES (like pumped hydro) generally requires specialized geography for construction. Suitable sites do occasionally coincide with wind power generation, and the two technologies may make a very good match. Interestingly, the existing CAES plant in Germany is now being used to support wind generation in the area.

Na/S and VRB batteries are large-scale battery chemistries that have been recently developed in applications sized for tens of MW. Both have been used and proposed in wind applications; VRB, in particular, has been used in relatively large-scale wind power applications in Japan. While they are significantly more expensive than pumped hydro and CAES, and are relatively immature technologies that have only recently been commercialized, they may be suitable for wind sites in which neither of the other technologies can be used.

Large-scale lead-acid batteries have also been used as energy storage for wind applications with some success. These batteries are generally not used for bulk storage, however, because of perceived costs and inconveniences with respect to replacement and maintenance. Other storage technologies, including flywheels and ultracapacitors, may be effective for short-duration wind applications such as fluctuation suppression. Additionally, several technical, economic, and environmental factors must be considered when selecting a storage technology. Such factors include—

- **Power level and duration:** At present, most energy storage products are probably best-suited for relatively small power levels (up to 100 MW) and relatively brief durations (up to seven or eight hours). Higher power levels and longer durations are more difficult to sustain at present, because the complexity of energy storage increases rapidly with size. CAES may be an exception to this observation, as it can be sized for several hundred MW.

- **Size and configuration of the local grid:** The optimal location and size for energy storage is heavily dependent on the characteristics of the local grid. A detailed study of the generation mix and load flow on a grid is the first step in determining whether an energy storage system makes sense and the configuration in which it must be constructed to provide optimal value.

- **Site geography:** The geography of the site will determine whether pumped hydro or CAES facilities can be sited there.

- **Tariff rates and penalties:** The extra value added by an energy storage system also depends on the regulatory environment. In a deregulated environment with a market for ancillary services, the energy storage system may be able to bring in additional revenue streams by selling these services.

- **Available subsidies and tax credits:** Subsidies and tax credits for energy storage systems (such as those enacted recently in the 2005 energy bill) may make the construction and operation of energy storage systems more cost-effective.

- **Environmental impact of the technology at the site:** Environmental conditions may place limitations on some advanced batteries or other technologies containing potentially hazardous materials.

Generally, a customer-specific analysis is necessary to determine which technologies are most likely to be cost effective. The table below provides a general idea of which technologies are most appropriate for several common applications.

Application	Energy Storage Technology							
	Lead-Acid Batteries	Nickel-Cadmium Batteries	Sodium-Sulfur (NAS) Batteries	Vanadium Redox Flow Batteries (VRB)	Flywheels	Ultracapacitors	CAES (10 MW, above ground)	CAES (300 MW, below ground)
Curtailment Reduction (TC)							**M**	✓
Time-Shifting (TS)							✓	✓
Forecast Hedging (FH)			**M**				✓	✓
Grid Frequency Support (GFX)	**M**	**M**						
Fluctuation Suppression (FS)					**M***	**M***		
TC + GFX + RC			**M**	✓			✓**	✓**
TS + GFX + RC			✓	**M**			✓**	✓**
FH + GFX + RC			✓	✓			✓**	✓**
FS + GFX + TS			✓	**M**			✓**	

* M* denotes potential for less demanding duty cycle see footnote, p. 3-5.

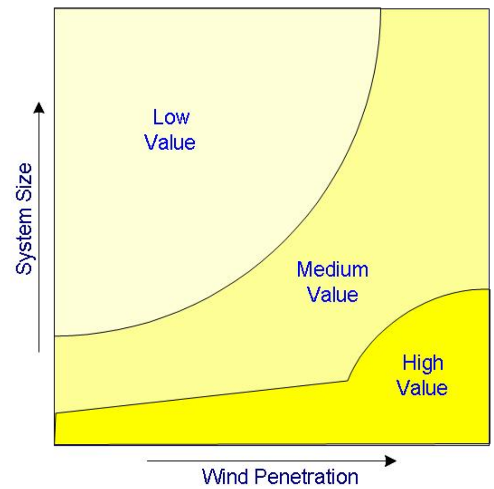
** ✓** denotes that the GFX application is excluded

Adapted from Energy Storage for Grid-connected Wind Applications (EPRI 1008703).

Wind-power Applications for Bulk Energy Storage

Several energy storage applications are of particular interest in view of the requirements of wind energy. One such application is transmission curtailment reduction, in which energy produced during times of transmission congestion is stored for delivery later. This is particularly applicable to wind farms, which are typically located far from load centers. Bulk energy storage can mitigate the need for adding additional transmission capability while avoiding the waste that occurs when the energy supplied by the renewable resource exceeds the ability of the grid to dispatch it. Energy storage may be cheaper and faster to build than additional transmission capacity, and may bring benefits even if additional transmission assets become available later. Energy storage can also be used to store energy produced during periods of low demand and deliver it during periods of high demand. Long-term storage can be used to hedge wind forecasts by providing reserve power when real-time wind generation falls short of the amount of generation bid for delivery. Shorter duration storage can be used to help maintain grid frequency in the face of imbalance in generation or load. This is particularly important for wind generation, which may rise or fall unpredictably. Finally, energy storage has also been proposed to even out very short duration fluctuations (on the order of seconds) caused by rising and falling wind.

Cost vs. Value



In general, the economic benefits to be gained by adding storage to grid-integrated wind power include avoiding waste that occurs when generation exceeds transmission capacity, allowing the sale of energy at peak demand times, and providing ancillary services (*e.g.*, spinning reserve) that bring value to an energy storage system bought for another purpose. The high costs of energy storage, however, mean that it will be used only in situations where it brings a great deal of value. For strong (*i.e.*, large, stable) power systems, or where wind does not have deep penetration, energy storage makes less sense. Energy storage makes the most economic sense in areas where wind penetration is relatively large or where the power system is relatively small (see the figure at right). In these situations (*e.g.*, island systems), the intermittency of wind-power generation makes it difficult to balance generation and load on the system, a problem that can be addressed through the use of energy storage. Additionally, in some markets the additional value gained by selling ancillary services, such as frequency regulation or spinning reserve, may aid in justifying the initial investment for an energy storage system.

Best Cases for Integrating Energy Storage with Wind Power

We have found four specific cases in which integrating energy storage with wind-power generation makes sense:

(1) Small power systems (power 'islands' and remote areas), in which the effects of wind variability can have substantial effect on grid stability. On larger grids, variability from a single wind farm is largely cancelled out by the aggregate strength of the grid; but smaller grids do not have as many resources to draw on.

(2) Areas with constrained transmission; that is, remote locations that do not have adequate transmission for the installed wind power. Energy storage can be used to reduce curtailment.

(3) Areas with special market structures, in which energy prices, penalties, costs, and market valuations of ancillary services are relatively high. In these situations, stored energy becomes more valuable, and energy storage used in wind applications can draw other revenue streams as well.

(4) Areas with pre-existing energy storage—pre-existing pumped hydro and CAES installations may bring more benefit when used for wind applications. The use of used or surplus batteries has also provided cost-effective storage for wind applications in certain cases.

Conclusion

In conclusion, we believe that, in the short term, energy storage is viable in certain highly specialized areas. For widespread application, however, the initial cost must decline in concert with the maturation of the vendor infrastructure.