ENERGY STORAGE—A KEY ENABLER OF THE SMART GRID

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ADVANCED BATTERIES - THE SMART GRID'S KILLER APPLICATION

Of the variety of energy storage technologies that could support a smart grid, advanced batteries may offer the broadest potential. Superconducting Magnetic Energy Storage (SMES), Compressed Air Energy Storage (CAES), and pumped hydroelectric storage all have value as large central station energy storage technologies, but are not well suited to also support smart distribution system applications.

Advances in the power electronics that convert DC power to AC have helped make battery storage systems increasingly reliable. And recent breakthroughs in advanced battery energy storage have shown the ability to deliver 5,000 to 10,000 charge/discharge cycles, or more. Advanced battery systems that trim daily peaks (requiring at least 365 cycles per year) could last more than 10 years, and perhaps up to 30 years. In addition, there is the growing need for advanced batteries to store wind energy produced primarily during off-peak hours, and solar energy produced during shoulder hours, for subsequent on-peak consumption. These renewable applications will require 200 to 300 cycles per year. Also, when the renewables are not available, the battery could be used for arbitrage (buying low cost energy at night and selling it during periods of high energy price) adding another 100 to 200 cycles per year.

The cost for certain advanced battery technologies has decreased by more than 50 percent, down to $2,000/kW for a 7 to 8 hour battery, making it possible for these systems to provide an attractive return on investment when multiple value streams are monetized (e.g., shifting renewables from off-peak to on-peak, credit for capacity with use of a 7-hour battery, shaving daily peaks, increasing T&D asset utilization, etc.).

Compared with using traditional technologies to meet a given system loss-of-load probability (LOLP), the total installed capacity requirements of battery energy storage will be attractive. Since the storage solution is highly modular, a maintenance or forced outage of any individual component, such as an individual battery storage cell, will not usually have a noticeable impact on overall plant availability, which can therefore approach 100 percent.

Storage is perhaps the most important smart grid advanced component because of its key role in complementing renewable generation. With the proper amount and type of storage broadly deployed and optimally controlled, renewable generation can be transformed from an energy source into a dispatchable generation source. And with the addition of energy storage, more wind and solar generation can be added to a typical power system that employs a large percentage of slow-response fossil and nuclear generation. It is possible that, with the addition of sufficient energy storage, the penetration of renewables can be significantly above 20 percent.

The desire to store inexpensive renewable energy will only increase. As the cost of natural gas used for peak generation by combustion turbine peakers or combined cycle units increases, the value of energy storage will continue to improve. Most importantly, the goal to reduce carbon emissions will encourage development of both renewables and storage.

As an added driver, environmentally benign battery systems are becoming achievable today. Advanced battery energy storage systems are being developed that, in the event of an accident, would be no more damaging than spilling rancid butter or soda. The resultant ease of siting such systems will lead to their wide-scale distribution, down to community and even to residential voltage levels. This will enable the use of advanced battery energy storage systems to not only meet conventional residential and commercial peaks, but to also support the rapid charging of plug-in hybrid electric vehicles (PHEVs) and other electric vehicles (EVs) without requiring the replacement of existing distribution line facilities, especially distribution station and line transformers.

BENEFITS OF SMART GRID/ ADVANCED BATTERY INTEGRATION

The smart grid, with its many advanced communications and control features, will make it possible to integrate the application of widely dispersed battery storage systems.

These systems can then be treated as a single huge resource serving multiple applications that offer the following potential benefits:

- Deferral of T&D equipment upgrades and replacements.
- Avoidance of combustion turbines, by providing dispatchable, local stored energy sources (demand charges can be reduced or capacity credits can be obtained from independent system operators and regional transmission operators).
- Reduced ramping impacts (both wear and tear, as well as reduced efficiency) on fossil generators caused by renewable generation's intermittency, due to sudden wind and cloud cover changes.
- Shifted wind energy, from primarily off-peak generation, to meet daily peak needs.
- Shifted solar energy from shoulder hours (particularly in the mid and eastern United States) to meet daily peaks that tend to occur at 5 p.m. to 7 p.m.
- Provision of arbitrage opportunities by allowing load serving entities (LSEs), or even consumers, to buy and store low cost energy during off-peak periods to displace much higher cost generation during peak periods.
- Provision of ancillary services such as high-cost frequency regulation, as well as spinning reserve and black start capacity.
- Reduced T&D line congestion and reduced electrical losses on the T&D system, by placing batteries at T&D interfaces, on distribution circuits or next to customers.
- Improved power quality and reactive power dispatch, enabled by high speed, flexible power electronic battery-to-grid interfaces.
- In some situations, improved voltage recovery after a fault, as well as possible avoidance of voltage collapse (storage facility inverters can provide short time, maximum reactive power output to mitigate a potential voltage collapse).
- Provision of a readily available source that can be installed in small increments to exactly match load growth—rather than adding large increments of new peaking combustion turbines—and with installation in months instead of years.

- Rapid charging of PHEVs or EVs, without expanding the existing distribution system.
- Provision for islanding of a grid into multiple micro-grids. The overall reliability of service to the end-user can be significantly improved with modular batteries distributed throughout the grid:
    - During emergency situations such as hurricane, tornado, or ice storm aftermaths, batteries have the capability of self-dispatching to meet local load, thus improving LSE reliability and safety. The batteries in a smart grid can provide limited local energy over a period of time (8 hours or more) without such concerns as fuel availability, emissions, noise, and safety normally associated with diesel and customer-owned generators.
    - Batteries can provide back-up energy to critical customers during an outage that causes the customer to be islanded or to all customers served by opened radial feeders. Improved system reliability equates to reduced societal costs of momentary and sustained outages.
- Provision of transient stability support for very weak networks.
- Provision of multiple environmental benefits by displacing peaking combustion turbines, enabling renewable generation, and reducing T&D losses.

Multiple Value Streams from these complementary applications can be realized with the proper placement and location of advanced energy storage systems. Many of the benefits noted above can be achieved simultaneously.

For example, an advanced battery sited at a substation whose transformers are nearing overload conditions can have several uses and benefits. By employing the appropriate smart grid controls, that single battery could be used to trim the transformers’ daily peaks, provide arbitrage benefits, reduce line congestion, provide capacity credits or trim the LSE system peaks, provide frequency regulation when needed, and manage the intermittency of renewables, while shifting wind and solar generation from off-peak or shoulder hours to on-peak periods.

CURRENT BATTERY OPTIONS

Currently four advanced battery solutions are most commonly deployed:

1. Sodium Sulfur (NAS) battery

The NAS battery operates at 300 °C, employing an electrochemical reaction between sodium and sulfur. Molten sulfur at the positive electrode and molten sodium at the negative electrode are separated by a solid beta alumina ceramic electrolyte. The electrolyte allows only the positive sodium ions to pass through it and combine with the sulfur to form sodium polysulfides. During discharge, sodium ions in the negative electrode pass through the solid electrolyte to reach sulfur in the positive electrode. A key issue is that the battery cannot be allowed to cool down, as the sodium and sulfur will solidify and damage the battery (note the Genset, in Figure 1, required for backup power). Therefore, the total installation must include the cost for backup generators that are installed to keep the battery hot even during a major outage on the grid. The need to maintain high NAS battery temperatures also has an impact on efficiency due to the total parasitic losses (though this is not an issue when the battery is used daily).

The batteries are sealed to protect them from moisture, which would cause the sodium to combust. And because the sodium polysulfides are highly corrosive, each cell is enclosed by a steel casing to protect it from corrosion. For bulk storage applications, the cells are arranged in blocks to provide better heat conservation and are encased in a vacuum-insulated box. Sand serves both as packing material and heat sink.

The basic NAS battery “building block” has a capacity of 50 kW. Batteries can be connected together to provide megawatts of power. A 1-MW system would be roughly the size of two semi-trailers and would weigh approximately 88 tons. The batteries will last for at least 15 years, assuming 2,500 charge/discharge cycles. The NAS battery has a high volumetric energy density.

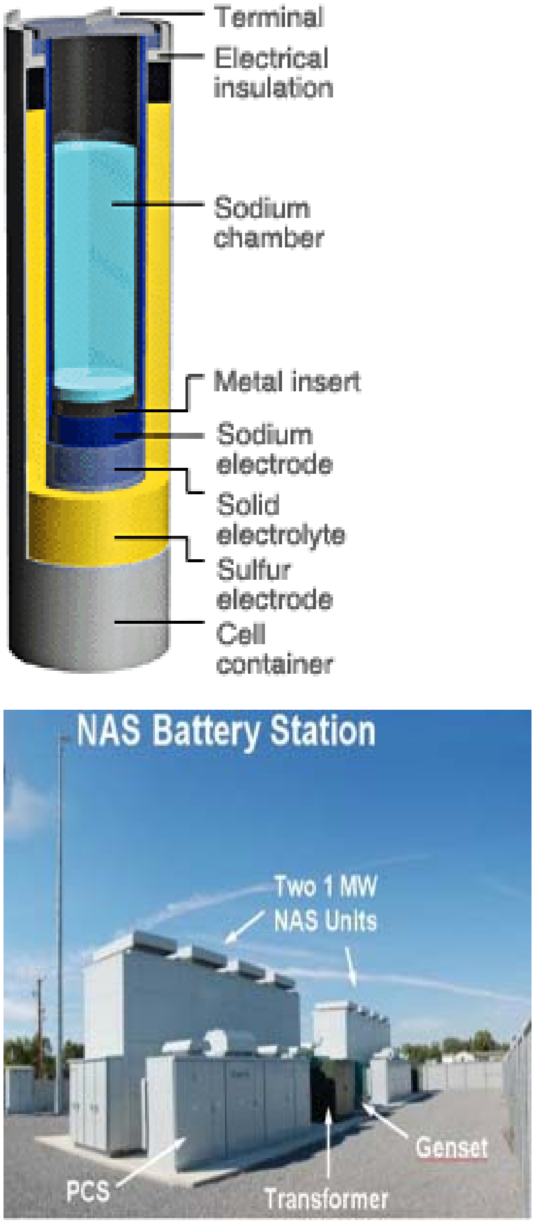
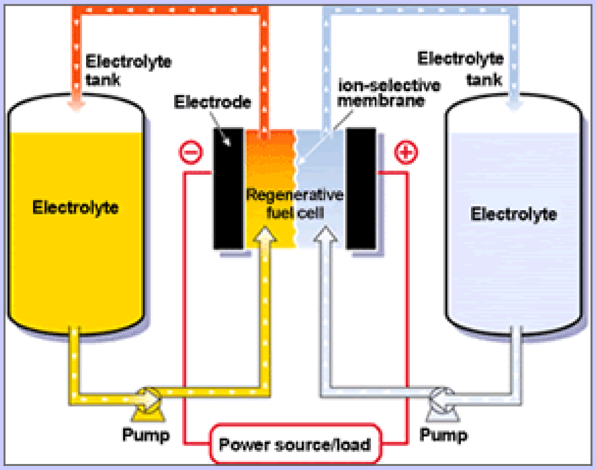


Figure 1: A NAS cell and two MW NAS units. (Photo courtesy of NGK & ESA).

According to the Energy Storage Association, the NAS battery technology has been demonstrated at over 190 sites in Japan totaling more than 270 MW with stored energy suitable for 6 hours daily peak shaving. The largest NAS installation is a 34 MW, 245 MWh unit used for wind stabilization in Northern Japan. U.S. utilities have deployed 9 MW for peak shaving, backup power, firming wind capacity, and other applications. Project development is in progress for an equal additional amount; several projects are underway in Europe and Japan. The U.S. annual capacity is currently 90MW, with 150 MW planned in 2010.

2.Vanadium Redox Battery (VRB):



Flow Battery Schematic

Source: U.S. Department of Energy

Figure 2: Flow battery schematic for vanadium redox battery.

The VRB is a flow battery that uses liquid vanadium-based electrolytes, stored in external tanks that flow into a regenerative power cell, producing electric power electrochemically. A key advantage of the VRB is that more energy can be stored by simply increasing the size of the electrolyte tanks. The power rating is a function of the regenerative fuel cell and its inverter. Flow batteries have a very low rate of internal discharge and parasitic losses. The VRB has an estimated life of more than 10,000 cycles. An issue with the VRB is its relatively low volumetric energy density, thus a sizeable footprint will be required. Improvements in the battery's membrane and electrolyte technologies are needed to reduce VRB capital cost.

3.The Zinc Bromide (ZnBr) battery

In this system, electrolyte is pumped from two electrolyte reservoirs through the battery block in two circuits, one for anode half-cells and the other for cathode half-cells.

The electrolyte in the anode loop is the anolyte; the electrolyte in the cathode loop is the catholyte. The anolyte and catholyte are in contact through microporous cell separators. Although ionic components in the electrolyte can readily pass through the cell separator, bulk mixing of anolyte and catholyte is prevented.

A fully integrated system is available that comprises energy storage, power conditioning, system control, and thermal management subsystems in a packaged, portable, turn-key, building block that can be placed wherever it is needed for immediately dispatchable online energy storage.

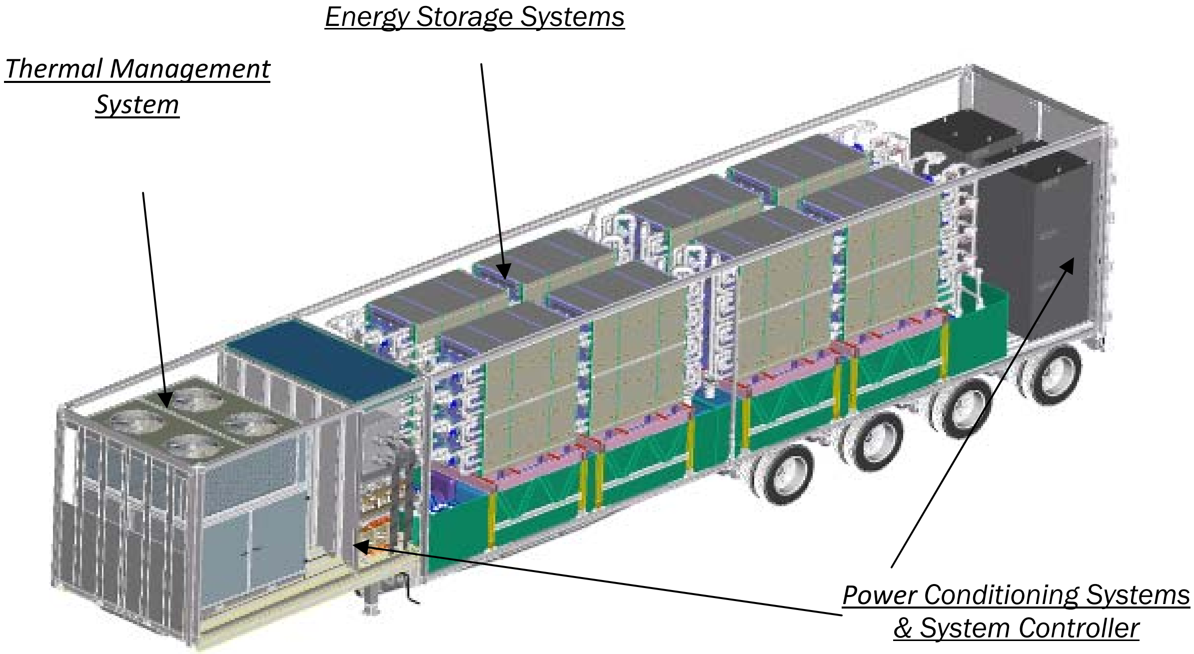


Figure 3: A fully integrated system.

Each system:

- Can deliver 500 kW of capacity and 2.8 MWh of energy at just under the legal weight limit, coming in at 108,000 pounds. A tanker with additional electrolyte can add more electrolyte at low incremental cost to increase the storage to 3.7 MWh or 7.4 hours
- Is packaged on a tractor-trailer that can remain a mobile asset capable of being hauled to any site.
- Is configured to allow multiple units to be automatically paralleled for higher power or greater energy storage requirements.

The overall system comprises four main subsystems:

- **Energy Storage Subsystem**—Including the energy storage blocks, electrolyte tanks, and circulation system.
- **Power Conditioning Subsystem**—Including four 125 kW grid-tied inverter/rectifiers and grid interconnections.
- **System Controller**—Providing real-time monitoring, control, management, and communication. This system includes an energy management application that manages the charging and discharging based on user settable parameters.
- **Thermal Management Subsystem**—Providing active thermal management to maintain optimum temperature for all system components. The thermal management makes use of a chiller mounted at one end of the trailer. The electrolyte reservoir contains a liquid-to-liquid heat exchanger used to remove heat during charge.

4.Lithium Ion (Li-ion)

In the lithium ion battery shown in Figure 4, the cathode is a lithiated metal oxide and the anode is made of carbon.

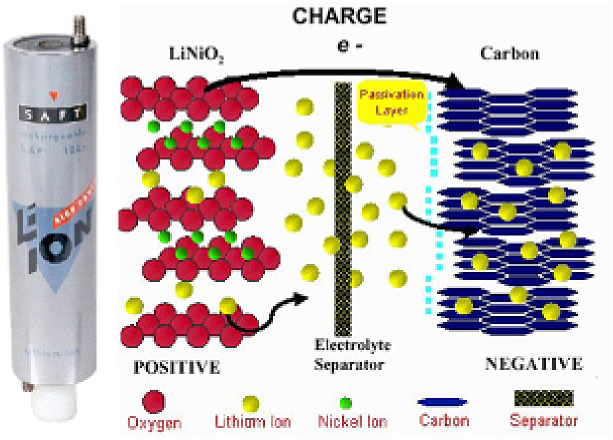


Photo Courtesy of SAFT America

Figure 4: A Lithium Ion battery also known as the Li-ion battery. (Photo courtesy of SAFT America and the Energy Storage Association.)

The electrolyte is made up of lithium salts dissolved in organic carbonates. When the battery is being charged, the lithium atoms in the cathode become ions and migrate through the electrolyte toward the carbon anode, where they combine with external electrons and are deposited between carbon layers as lithium atoms. This process is reversed during discharge. Though the Li-ion battery is the battery of choice for laptops and vehicles because of its very high energy density (on a weight basis), the key issues for utility applications are its high costs (>$600/kw-hr or over twice the cost for a ZnBr battery) and cycle life (2,000–5,000 cycles). On the positive side, Li-ion efficiency is very high, potentially over 90 percent. But for most utility storage applications, the high cost and cycle life are major barriers. AES has installed and tested on Indianapolis Power & Light’s power grid a 2-MW 500-kWh (15 minutes of storage) Altairnano Lithium Titanate battery, which has the capabilities of both a battery and a super capacitor (allowing for rapid charge and discharge) for frequency regulation.

The tables below summarize the attributes of each advanced battery energy storage technology mentioned above. The economics of energy storage is improving as shown in these tables, which also present the battery cycle life, round trip efficiency, environmental impact, energy density, and other major grid application issues.

Table 1– Advanced Battery Technology Characteristics			
Advanced Battery Type	**Capital Costs $kW-hr**	**Life Cycle Number of charge/discharge cycled to 80% DOD**	**% Round Trip Efficiency AC to AC**
Li - ion	**Very High ($600 – $1,200/kW-hr)**	**Medium (2,000–5,000)**	**Very High (85% to 95%)**
VRB	**Medium ($350 – $500/kW-hr)**	**High (up to 10,000)**	**Medium (70-75%)**
NAS	**Medium ($350-- $500/kW-hr)**	**Medium (3,000–5,000)**	**High (85% to 90%)**
ZnBr	**Low ($150-- $250/kW-hr)**	**High (>10,000)**	**Medium (70-75%)**
Comments	**Note that costs do not include cost of installation which adds about 20% to 30% to the cost depending on size of installation**	**For storing wind or solar, cycle lives of 10,000 or greater will be needed (300 to 500 cycles a year times 30 years)**	**Efficiency is important for arbitrage but less so for peak shaving, frequency regulation, etc.**

Table 2 – Additional Advanced Battery Technology Characteristics			
Advanced Battery Type	**Environmental impact (ease of permitting)**	**Energy to size Energy Density Wh/L**	**Other Issues or disadvantages**
Li - ion	**Low**	**Medium (80–200 Wh/L)**	**High self-discharge rate and requires special charging circuit**
VRB	**High**	**Low (15–25 Wh/L)**	**Potential environmental concern and permitting difficulties**
NAS	**Medium**	**High (145–150 Wh/L)**	**Safety concerns addressed by design; backup generator required**
ZnBr	**Low**	**High (130–150 Wh/L)**	**Energy density is a big issue for transportation**
Comments		**Energy density is not an issue unless the cost of land is high, as in urban locations**	

THE CONTINUING QUEST FOR AN IDEAL STORAGE DEVICE

Research programs continue to search for the ideal storage device.

A better battery in the transportation sector, for example one that has high energy density and portability and can accommodate many thousands of charge/discharge cycles, could be all that is needed to break America's addiction to oil and to allow a new fleet of millions of PHEVs that can also serve as energy sources to the grid. However, an ideal battery for the transportation sector may not translate into an ideal battery for the stationary utility market sector. The ARRA has allocated 2 billion dollars for research into new battery and advanced vehicle solutions.

SUMMARY

For decades, this industry has argued that electricity differs from all other products and markets because it cannot be stored.

This has been basically correct, but future developments have the potential to remove this unique constraint and to combine storage with other smart grid technologies to create a new energy paradigm. Electric batteries may offer the greatest potential as a smart grid enabler. Four advanced battery designs are currently being deployed to serve a variety of transmission and distribution applications, with multiple benefits potentially flowing from a single installation. Research continues to seek out new chemistries and physics that will provide the breakthrough low cost storage medium that will indeed be the smart grid's killer application.

For more information

This document is part of a collection of documents prepared by the Modern Grid Strategy team. Documents are available for free download from the Modern Grid website.

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