

Appendix F. Energy Storage Technologies

Energy Storage Technologies – Description and Status Report

As the various technologies evolve, energy storage will likely have many applications and offer potential benefits to both transmission and distribution systems. Each energy storage technology will likely have its own niche depending on the operating characteristics that define the device. Performance and cost ultimately determine which type of storage is right for which applications. These applications include:

- Integration of intermittent renewable energy
- Frequency regulation
- Peak load management and system reliability
- Smart Grid deployment
- Power quality

Pumped Hydro

Pumped hydro facilities use off-peak electricity to pump water from a lower reservoir into one at a higher elevation. When the water stored in the upper reservoir is released, it is passed through hydraulic turbines to generate electricity. The off-peak electrical energy used to pump the water up hill can be stored indefinitely as gravitational energy in the upper reservoir. Thus, two reservoirs in combination can be used to store electrical energy for a long period of time and in large quantities.

Additional advantages of pumped hydro are when the water is released through a turbine during times of peak demand, low-cost power, frequency regulation of the grid, and reserve capability are provided.

In 2010, a Canadian-based firm (Riverbank LLC) filed a preliminary permit application with the Federal Energy Regulatory Commission (FERC) to study the feasibility of a \$2 billion, 1,000-megawatt underground hydroelectric plant in Chippewa County, Minnesota, near Granite Falls. The project developer

estimated the time frame between preliminary permitting to construction to be 8-12 years.

Compressed Air Energy Storage (CAES)

CAES systems use off-peak power to pressurize air into an underground reservoir – salt cavern, abandoned hard rock mine, or aquifer – which is then released during peak daytime hours to power an expander type turbine/generator for power production. Today, CAES is the only other commercially available technology besides pumped hydro able to provide very large system energy storage deliverability to use for commodity storage or other large-scale setting.

Testing and analysis of the ability to store the air underground is being conducted at potential locations at the Iowa Stored Energy Park (ISEP) in Dallas Center, Iowa. When the results from the studies are completed, the project will move into the design phase, with procurement and construction to follow. It is anticipated the ISEP will become operational in 2011.

Recently, several DOE stimulus grants were awarded for energy storage demonstration projects involving CAES: a 300 MW plant in California using a saline porous rock formation; a 150 MW plant using an existing salt cavern in New York; and a 1 MW/4hr system that will utilize above-ground industrial pressure facilities and hydraulic compression and expansion coupled with isothermal gas cycling.

Flywheels

Flywheel energy storage works by accelerating a cylindrical assembly called a rotor (flywheel) to a very high speed and maintaining the energy in the system as rotational energy. The energy is converted back by slowing down the flywheel. The flywheel system itself functions as a kinetic, or mechanical battery, spinning at very high speeds to store energy that is instantly available when needed.

Modern flywheels use composite rotors made with carbon-fiber materials. The rotors have a very high strength-to-density ratio, and rotate in a vacuum chamber to minimize aerodynamic losses. The use of superconducting electromagnetic bearings can virtually eliminate energy losses through friction.

Flywheels are able to charge and discharge rapidly, and are little affected by temperature fluctuations, making them ideal for frequency regulation, cloud mitigation for solar PV, ramp mitigation for wind and other services. They take up relatively little space, have lower maintenance requirements than batteries, and have a long life span. Flywheels are relatively tolerant of extreme operation - the lifetime of a flywheel system will not be shortened by a deep discharge. A disadvantage of flywheel technology is that power loss is faster than for batteries.

Beacon Power Corp plans to build a flywheel storage plant in New York that will store 20 MW of electricity in 2,500 flywheels. The company was recently awarded a DOE stimulus grant to build another 20 MW plant in Chicago.

Batteries

Batteries, which store energy in the form of chemical energy, are the most common device used for storing electrical energy. Advancements in battery technology over the last 20 years have been driven primarily by the use of batteries in consumer electronics and power tools. Only in the last ten years, with efforts to design better batteries for transportation, have possible uses of battery technology for the power grid emerged. More efficient cost-effective power electronics have helped make potential utility applications possible. For battery technologies to be practically applied in the AC utility grid, reliable power conversion systems that convert battery DC power to AC were needed. These devices now exist and have many years of service experience, which makes a wide range of battery technologies practical for grid support applications.

Specific battery types include:

- Lead-acid batteries

- Flow batteries
- Lithium-ion batteries
- Nickel-cadmium batteries
- Sodium sulfur batteries

Lead-acid Batteries. Lead-acid batteries are the most common type of battery in both utility and non-utility applications, and are the oldest and most mature of all battery technologies. The batteries are used in automobiles and as a backup energy source, such as uninterruptible power source (UPS) use and “black start” sources in power plants.

The traditional lead-acid battery is made up of plates, lead, and lead oxide immersed in a solution, called electrolyte, consisting of 35% sulfuric acid and 65% water. The solution causes a chemical reaction that produces electrons. Various other chemicals are also used to change the density, hardness, and porosity of the plates.

Valve-regulated lead-acid batteries, which are sealed and need no topping off with water, are common in distributed power applications. Gel-type lead-acid batteries are filled with a gel instead of liquid, making them much less likely to spill. These batteries are becoming popular in Europe.

A 40-MWh lead-acid battery was installed in the Southern California grid in 1988 to demonstrate the peak shaving capabilities of batteries in a grid application. The battery demonstrated the value of stored energy in the grid, but the limited cycling capability of lead-acid battery made the overall economics of the system unacceptable.

Flow Batteries. In flow battery technology, a central battery unit provides power, but total energy is furnished by a reservoir of rechargeable electrolyte, which can be as large as needed and situated where convenient. Flow batteries offer potentially higher efficiencies and longer life than conventional lead-acid batteries. Their construction is based on plastic components in the reactor

stacks, piping, and tanks for holding the electrolytes, so the batteries are relatively light in weight and have a longer life.

Three types of flow batteries are undergoing development and demonstration for distributed energy storage applications:

- Zinc-bromine batteries
- Vanadium redox batteries
- Sodium-bromine batteries

A number of DOE stimulus grants were awarded to energy storage demonstration projects involving flow batteries. The largest of these went to Boston-based Premium Power Corporation to install seven 500kW/6hr zinc-bromine storage systems in California, Massachusetts and New York and demonstrate their capability to lower peak energy demand and reduce the cost of power interruptions.

Lithium-ion Batteries. The lithium-ion battery is the battery technology with the broadest base of applications today. The technology can be applied in a wide variety of shapes and sizes and are light in weight relative to aqueous battery technologies, such as lead-acid batteries. These batteries are used in cell phones and laptop computers. Lithium-ion batteries have the highest power density of all batteries on the commercial market on a per-unit-of-volume basis. The continued development of the technology for Plug-in Hybrid Electric Vehicle (PHEV) application has resulted in newer types of lithium-ion cells with more sophisticated cell management systems to improve performance and safety.

The ancillary services market appears to be the best opportunity for lithium-ion batteries in utility power applications. As volume production increases, the future cost of the battery systems will play a key role in how fast they penetrate utility power applications. Two lithium-ion designs that are starting to be used in higher-power utility grid applications are lithium titanate and lithium iron phosphate. The lithium titanate design uses manganese in the cathode and titanate in the anodes. The other type uses iron phosphate in the cathodes and

is considered a safer technology because of reduced risk of fire in the battery cells, and because this design is more resistant to overcharge when operated in a range of up to 100% state of charge.

Several DOE stimulus grants were awarded for energy storage demonstration projects involving lithium ion battery technology. Southern California Edison received a grant to build and evaluate an 8MW battery (using racks of smaller batteries) to improve grid performance and aid in the integration of wind generation. Seo, Inc. received a grant to help develop and deploy a new class of lithium ion batteries targeted for utility-scale operations, particularly for Community Energy Storage projects. Nickel-cadmium Batteries. Nickel-cadmium (Ni-Cad) batteries have gained a reputation as a rugged, durable stored energy source with good cycling capability and a broad discharge range. These batteries have been applied in a variety of backup power applications and were chosen to provide “spinning reserve” for a transmission project in Alaska, which involves a 26 MW Ni-Cad battery rated for 15 min. Ni-Cad batteries are used for utility applications, such as power ramp rate control for “smoothing” wind farm power variability in areas with weak power grids, such as island power systems.

Sodium Sulfur Batteries. The sodium sulfur (NaS) battery consists of sulfur at the positive electrode and sodium at the negative electrode as active materials, and a “beta alumina solid electrolyte” (BASE) of sodium ion conductive ceramic, which separates both electrodes. This hermetically sealed battery is operated under the condition that the active materials at both electrodes are liquid and its electrolyte is solid.

When a load is connected to the terminals, electric power is discharged through the load. During the discharge, sodium ions converted from sodium in a negative electrode pass through solid electrolyte then reach to sulfur in the positive electrode. The electrons finally flow to outside circuits. The electric power is generated by such current flow. With the progress of the discharge, sodium polysulfide is formed in positive electrode; on the contrary, sodium in negative electrode will decrease by consumption. During the charge, the electric

power supplied from outside form sodium in negative electrode and sulfur in positive electrode by following the reverse process of the discharge. Because of this, the energy is stored in the battery. The battery operates at about 300°C. NaS battery cells are about 89% efficient and the battery system is capable of six hours of discharge time on a daily basis.

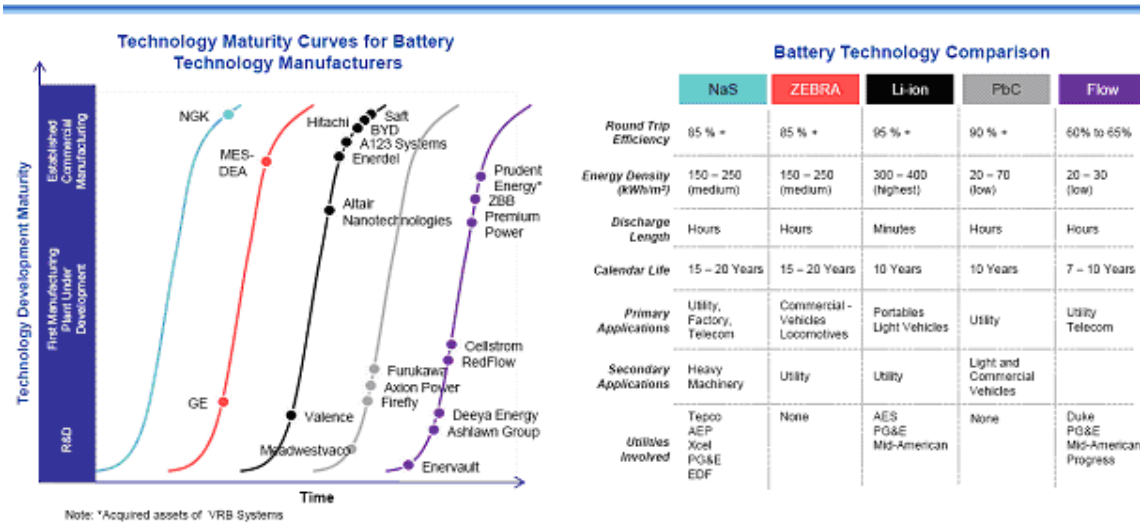
NaS battery technology for large-scale applications was perfected in Japan. The most significant wind-firming project is the Rokkasho Wind Farm installation in the Aomori prefecture, Japan. 34MW of NaS batteries are being installed on the 51MW wind farm to firm up the intermittent output of wind generation. Trial operations began in May 2008. The world's first PV power generation system using a NaS battery is installed at the Wakkanai test and research facility in Hokkaido prefecture, Japan. The solar firming research is combining 5 MW solar with 1.5 MW NaS battery to study the effect battery storage has on firming up the variable PV solar output and extending the combined output to cover the peak load window. In the United States, American Electric Power has installed 7 MW of the bus-sized batteries to ease congestion on its transmission lines and has an additional 4 MW under development.

In addition, Xcel Energy is testing a 1 MW NaS battery to manage wind power in Minnesota. This project tests a 1 MW batter energy storage system connected directly to a wind farm in an effort to store wind energy and return it to the grid. It is expected to demonstrate long-term emission reductions from increased availability of wind; help reduce impacts of wind variability; and allow the Company to meet the Minnesota Renewable Energy Standard.

The following table in Figure XX shows that NaS and flow batteries are the most mature battery technologies for utility-scale applications, but Li-ion is gaining traction.

Figure G.1
Battery Technology Maturity

Battery Technology Appeal Broadens As Renewables Grow



NaS and flow batteries are the most mature battery technologies for utility-scale applications, but Li-ion, increasingly popular for electronic devices and transportation uses, is gaining traction

Source: IHS Emerging Energy Research

Hydrogen

Off peak electricity is used to electrolyze water to produce hydrogen, which is stored either in compressed gas tanks or in underground geologic formations. The hydrogen is then reconverted back into electricity using a polymer electrolyte membrane (PEM) fuel cell or hydrogen combustion turbine. If the system uses electricity generated from off-peak wind or solar energy, it can produce virtually emission-free hydrogen. Electrolysis is defined as ‘splitting apart using an electric current’. Energy is supplied from an external source, such as wind or solar, to drive the electrochemical reaction and run the balance of the plant. An electrolyzer uses direct current (DC) to separate water into its components – hydrogen and oxygen. Hydrogen is fed to the anode where a

catalyst separates hydrogen's negatively charged electrons from positively charged ions (protons). At the cathode, oxygen combines with electrons and in some cases protons or water resulting in water or hydroxide ions, respectively.

For PEM fuel cells, protons move through the electrolyte to the cathode to combine with oxygen and electrons, producing water and heat. The electrons from the anode side of the cell cannot pass through the electrolyte to the positively charged cathode; they must travel around it via an electrical circuit to reach the other side of the cell. This movement of electrons is an electrical current.

The *Wind-to-Hydrogen Project (Wind2H2)* is a collaboration between Xcel Energy and NREL at the National Wind Technology Center in Boulder, Colorado to use solar and wind energy to produce and store hydrogen. The stored hydrogen can be used both as a transportation fuel and as an energy storage medium, effectively allowing renewable energy to be stored and converted back to electricity at a later time using a hydrogen internal combustion engine or fuel cell. The University of Minnesota West Central Research and Outreach Center (WCROC) is using a “wind to hydrogen” technology to make renewable anhydrous ammonia, in partnership with Xcel Energy and other Minnesota stakeholders. Anhydrous ammonia is a common nitrogen-based fertilizer, currently made using natural gas.

Comparative Costs

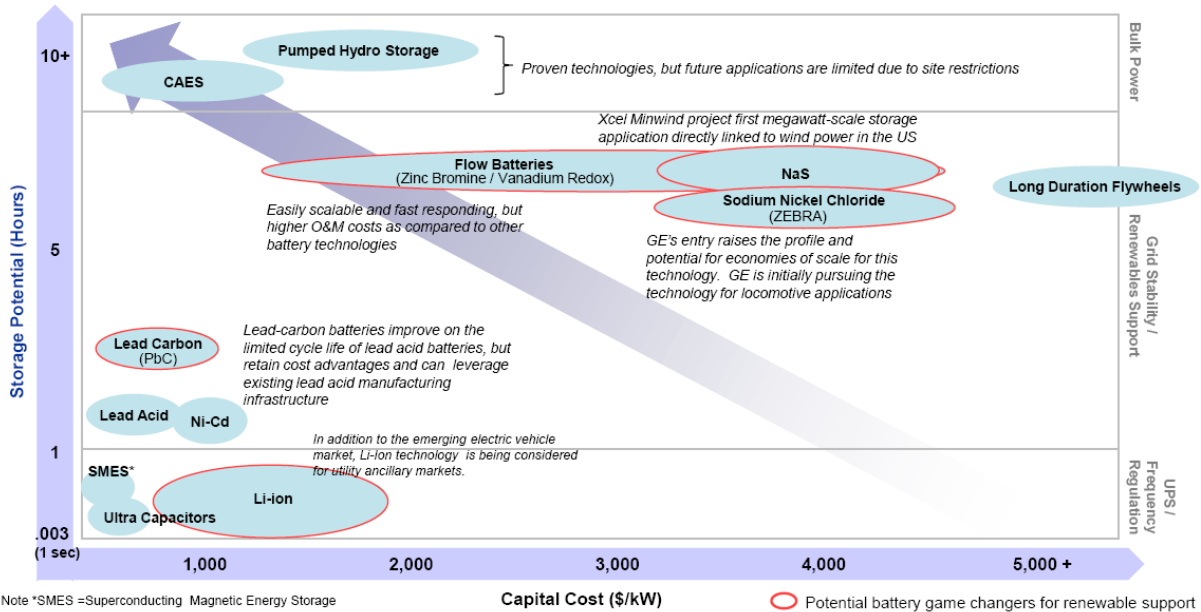
The following graph in Figure XX gives a sense for the comparative costs across the various storage technologies. The technology characteristics that most impact lifecycle costs include the initial capital cost, AC to AC efficiency, cyclability, operation and maintenance costs. As the performance characteristics of the various technologies are developed and improved, the commercial potential also improves, which may in turn bring down the initial capital cost as manufacturing scope and scale adapts to increased demand for the technology.

Figure G.2

Comparison of Storage Technology Cost and Potential

Battery Technology Appeal Broadens As Renewables Grow

Storage Technology Landscape



The storage market is still in a very nascent stage, with no clear technology leader. However, a variety of battery technologies hold promise for supporting renewable energy

Source: IHS Emerging Energy Research