Appendix E. Wind Storage Research and Experiments

Because Wind Resources will play such an important role in our future resource portfolio, we have two research projects currently in progress that have the potential to support wind resources. Additionally, we have been directed by the Commission to review the current state of wind energy storage research.

Absent the opportunity to market excess energy production off-system, at lower load levels, wind energy by 2020 will likely lead us to back down operations at some base load resources. Because it is impractical to quickly ramp base load units, the ability to store wind energy temporarily for use when loads are higher during on-peak periods would be very beneficial to system operations. The Midwest Independent System Operator ("MISO") is currently studying whether it is economic to make transmission infrastructure improvements sufficient to move this projected excess wind energy from Minnesota to the rest of MISO, but the results of those studies are not yet available.

In an effort to look at alternatives, we are currently experimenting with two storage technologies as discussed below. This is followed by a general discussion of other types of electric energy storage that could be used to store wind energy: large scale storage technology, scalable storage technology, and chemical conversion storage technology.

Current Experiments

Wind Storage Research and Development – NaS Battery System

NaS battery technology has been demonstrated at over 30 sites in Japan totaling more than 20 MW with stored energy suitable for 8 hours daily peak shaving. Xcel Energy is planning to explore the viability of coupling a 1 MW NaS battery installation with the 11.8 MW MinnWind wind project. The primary objective of this project is to understand the value of energy storage in supporting greater wind energy penetration on the Xcel Energy System by testing the hypothesis that energy storage will enable 'firming' of wind energy and a reduction in impacts from compensating for variability and limited predictability of wind generation resources and the associated emissions. Additional benefits of battery energy storage such as transmission and distribution grid system support, which are essential to integrating a much larger percentage of wind energy into the regional energy resource mix will also be evaluated.

This project involves building a 1 MW, wind energy battery storage system, using sodium sulfur (NaS) battery technology. Wind energy stored within the battery system will be controlled and dispatched when needed for supply or for transmission system stability. The battery is capable of providing a constant power level of up to 1.2 MW for 6 hours. The battery energy storage system is projected to be operational by the fourth quarter of 2008. It is estimated that the testing phase will be completed at the end of 2009, with associated findings and recommendations developed during the first half of 2010.

NaS technology has been selected for this project because of its high storage capacity, its ability to handle the large number of charge-recharge cycles associated with intermittent renewable energy sources, its large scale and potential for even larger scalability, its dynamic response to system changes, and its commercial availability.

Although the NaS battery technology is commercially available, it has not been connected to a wind application domestically and will require development of a power conversion system specific to this project. As such, the project may contribute to the standardization of the power conversion system and utility dispatch protocols, which would enable greater implementation on the electric grid and reduce overall capital costs.

Specific project goals include:

1. Evaluate the ability of large-scale battery-storage technology to effectively 'firm' wind energy, enabling a shift of wind-generated energy from off-peak to on-peak availability. This could theoretically increase

the value of wind-generated energy as well as decrease the need for intermediate and peaking facilities.

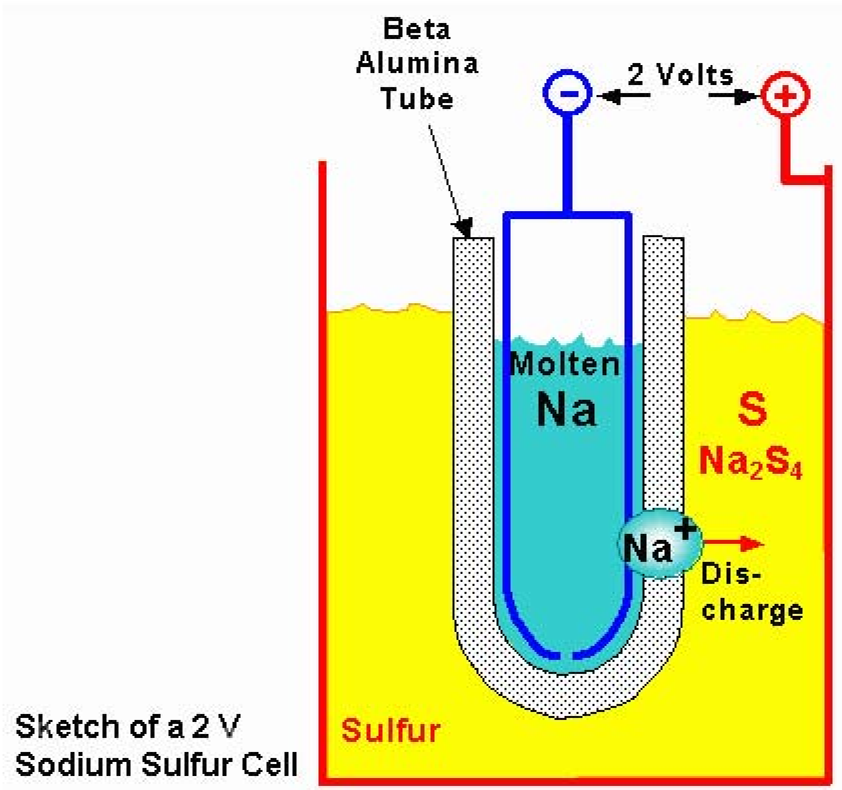
2. Evaluate the ability of battery-storage technology to reduce the need to compensate for the variability and limited predictability of wind generation resources. This includes reductions in carbon-based spinning reserves or supplemental reserve requirements, as well as reductions in contingency recovery costs, such as generator black start support.
3. Evaluate the potential for battery-storage technology to support the transmission system and therefore allow the system to more effectively integrate wind into system operations. This means the system would be able to maintain or maximize the integrity of the grid including frequency, voltage and reliability despite wind's intermittency. Grid support that could be provided by battery-storage technology may include reactive load support, grid frequency support, fluctuation suppression, curtailment management and throughput bottleneck relief.

The complete system will include the following integral components:

- *NaS Battery System:* The NaS battery system is modular in design. Each battery contains twenty 50-kw modules, which in turn each contain an array of 320 individual cells within a thermally insulated enclosure equipped with electric heaters to maintain the operating temperature at about 300ºC. Cells are closely spaced, connected in series and/or parallel, and packed in sand. A vacuum is drawn on the gap between the inner and outer walls of the enclosure lid to minimize heat loss. This modularity allows flexibility in configuring the system as well as ease of increasing the size of the system.

  The electrochemistry of the cell includes a solid beta alumina electrolyte made with a sodium ion conductive ceramic material, which serves as both the electrolyte and the separator between the sodium (-) and sulfur (+) electrodes. To ensure safety, the NaS cell includes a 'safety tube' inside the beta-alumina tube that controls the amount of sodium and sulfur that can potentially combine. This prevents generation of enough heat to rupture the cell.

Figure E-1



- *Power conversion equipment:* The power conversion equipment handles the interconnections between AC and DC power to and from the battery. There are a number of challenges that need to be addressed, such as low voltage ride-through capability, the role of power-electronics based transformers, and different topologies of the converters. During the project, we will be identifying the issues and looking at which can be addressed while providing the most value to the overall system efficiency and effectiveness in terms of supporting grid functionality and enabling more renewable energy on the grid.
- *Backup power for emergency battery temperature regulation:* The primary function of the backup power is to provide emergency backup to external heaters that

are needed to keep the battery maintained at an elevated temperature at all times to accomplish energy storage function. These heaters are only needed on battery start up or when the batteries are in an idle state. Backup power may come from either the wind farm's backup power or may be a separate diesel/gasoline-driven generator.

- *Grid interconnection*: Grid interconnections will need to meet requirements. Since this is a unique application, there may be challenges to be addressed, such as (1) providing functionality to switch back and forth from charging to discharging modes and (2) having the ability to provide ancillary services in addition to electric energy.
- *Wind farm interface*: The project will be examining options to determine the best approach to interfacing with the entire wind farm. The wind farm interface could be a common bus that all the wind turbines feed into, or there could be an interface at the bus of each individual turbine. The primary challenge here is designing the interconnection to the battery so that excess energy, over the 1.2 MW battery capacity, is 'passed through'. An alternative may be to use the wind turbine controls to suppress the wind when the rapid increase in wind power exceeds the battery's limits.
- *Local and remote performance monitoring equipment, data collection equipment, system control equipment, and associated communication equipment*: This equipment will be designed to remotely capture data from the project and make it accessible via the internet to the project partners for analysis. The data could also be made available to other interested parties.

The Company is currently considering filing for recovery of the costs of this program through its proposed RES Rider seeing the RES statute discusses battery technology as eligible for recovery under the rider.

Wind-to-Hydrogen Demonstration Project

The U.S. Department of Energy's National Renewable Energy Laboratory ("NREL") and Xcel Energy are working in partnership on a unique project to analyze and compare hydrogen production from wind power and the electric grid. This project will explore new synergies for hydrogen as an energy storage medium and a transportation fuel. Most importantly, the project aims to overcome the intermittent aspect of wind energy by enabling energy storage for later use when the wind isn't blowing or the demand for electricity is high. Energy storage systems have the potential for addressing electric system integration issues inherent with intermittent wind energy resources, thereby enabling higher amounts of wind power on the electric system.

Hydrogen can reduce our dependence on imported oil and benefit the environment by reducing greenhouse gas emissions and concentrations of criteria pollutants that affect air quality. Hydrogen produced using renewable resources results in virtually zero greenhouse gas emissions.

The hydrogen will be produced through electrolysis — the process of splitting water into hydrogen and oxygen using electricity. The hydrogen will then be compressed and stored for future use to produce electricity (through a fuel cell or a hydrogen internal combustion engine) for grid-connected peaking power applications, or, in the future, as a vehicle fuel.

This demonstration project aims to investigate ways to improve the system efficiency of producing, delivering and using hydrogen from renewable resources in quantities large enough, and at costs low enough, to ultimately compete with traditional energy resources such as coal, oil and natural gas.

- The project will use two wind turbine technologies: a Northern Power Systems 100 kW wind turbine and a Bergey 10 kW wind turbine. The wind turbines present different kW capacities to the project. Both wind turbines are variable speed in that the blades' speed varies with wind speed. Variable speed wind turbines produce alternating current ("AC") that varies in magnitude and frequency (known as 'wild' AC) as the wind speed changes.

- The energy from the 10 kW wind turbine will be converted from its 'wild' AC form to direct current ("DC"), then used by the electrolyzer stack to produce hydrogen and oxygen from water. The energy from the 100 kW wind turbine will be captured from its existing controller, which already powers a DC bus of nearly 800 V. That voltage is too high for the electrolyzer stacks, and new power electronics will be designed to make the necessary conversion.

- Two HOGEN 40RE proton exchange membrane (PEM) electrolyzers from Proton Energy Systems and one Teledyne HMXT-100 alkaline electrolyzer will be used to split water into hydrogen and oxygen gases. The project will examine issues surrounding the integration of both technologies as well as how to operate the electrolyzers of different product gas output pressures in parallel.

- The hydrogen will be compressed and stored. Then, a hydrogen internal combustion engine (or a fuel cell) will convert it to electricity during peak demand hours. The demonstration project will reveal integration and operational issues as well as identify opportunities for improvement and other potential benefits for consumers.

Project Benefits

- Exploring how to make hydrogen without producing greenhouse gasses or other harmful by-products. Currently, the primary means of manufacturing hydrogen is to strip it from natural gas (mostly methane) via steam methane reforming. However, technologies to produce hydrogen from non-fossil sources such as biomass, wind and solar also are available. Benefits of producing hydrogen from these non-fossil sources include eliminating greenhouse gas emissions. Also, unlike electricity, hydrogen can be stored quite easily.

- Creating synergies from co-production of electricity and hydrogen. By storing hydrogen for later use, the project addresses the intermittent nature of wind power, creating a ready source of electricity for periods when the wind isn't blowing or the demand is high. Additional synergies include consistent support of the electric grid via off-peak storage of hydrogen, and hydrogen production for potential vehicle use.

- Comparing multiple electrolyzer technologies including alkaline and a proton exchange membrane ("PEM") -- also called polymer electrolyte membrane -- electrolyzers to gauge their efficiencies and responsiveness to the variability of the wind.

- Achieving efficiency gains and potential system cost reductions though a unique integrated DC-to-DC connection between the wind turbine and the electrolyzers, the first time such a connection has been used.

Key challenges of the project

- Explore system level integration issues surrounding multiple electrolyzers of both PEM and alkaline technologies that also produce hydrogen gas at different pressures.

- Evaluate the ability to integrate energy from variable speed wind turbines directly to the hydrogen producing stacks of commercially available electrolyzers.

- Determine the system impacts and ability of each electrolyzer technology to accommodate the varying energy input from wind turbines.

- Quantify system-level efficiency improvements and cost reductions by designing, building and integrating dedicated wind to electrolyzer stack power electronics to enable the closer coupling of the electricity from wind to the requirements of the electrolyzer stack.

- Gain operational experience in a hydrogen production facility including the compression of hydrogen and the use of a hydrogen-fueled internal combustion engine to generate electricity during peak demand hours.

- Evaluate appropriate safety systems and system controls to assure safe operation of hydrogen production with varying wind energy input.

- Demonstrate operation of a "closely-coupled" wind-to-hydrogen system to enable evaluation of actual system costs to identify areas for cost and efficiency improvements.

- Explore operational challenges and opportunities related to energy storage systems and their potential for addressing electric system integration issues inherent with intermittent wind energy resources.

The initial system will be located at NREL's National Wind Technology Center near Boulder, Colorado. This site is ideally located for research and development testing of wind turbines and hydrogen systems because it experiences distinct wind patterns.

The project cost is about $2 million and Xcel Energy is funding approximately $1.3 million through its capital budget, including the components for producing and storing hydrogen. NREL and the Department of Energy will invest approximately $750,000 in the project. After the demonstration is completed, Xcel Energy plans to move the equipment for commercial application someplace on its system.

Other Available Technologies

Pumped Storage

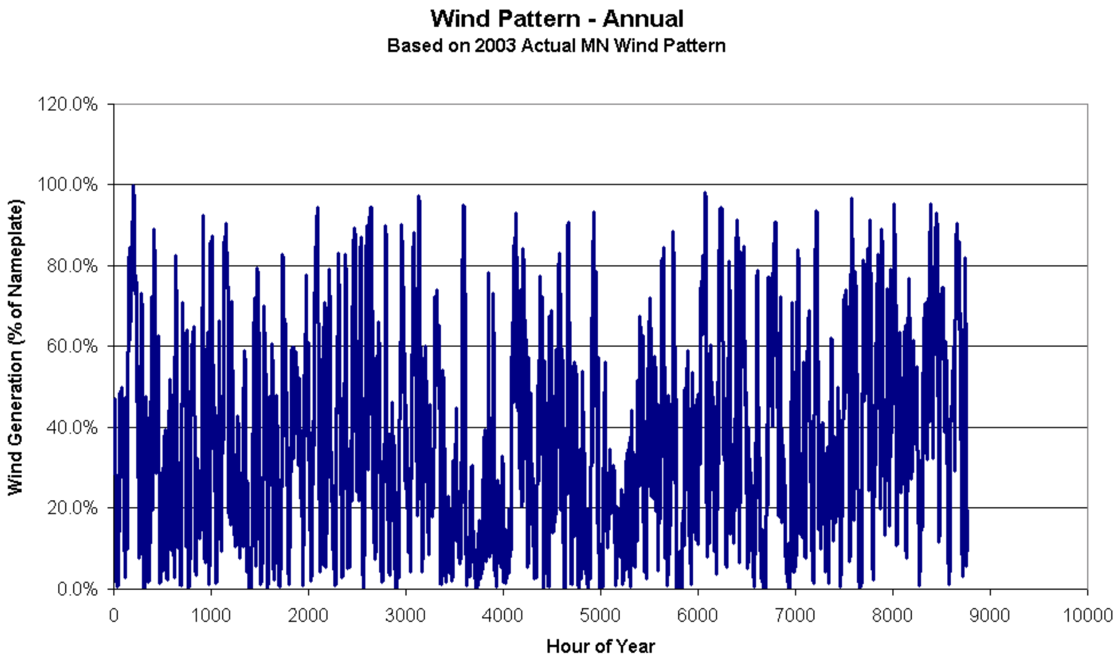
Conventional pumped storage technology uses two water reservoirs, separated vertically. During off-peak hours, water is pumped from the lower reservoir to the upper reservoir. When required, the water flow is reversed to generate electricity. Some hydro plants have a storage capability and can be dispatched as a pumped hydro facility. Underground pumped storage, using flooded mine shafts or other geological cavities, are also technically possible.

Pumped storage was first used in Italy and Switzerland in the 1890's. By 1933 reversible pump-turbines with motor-generators were available. Adjustable speed machines are now being used to improve efficiency. Pumped storage is available at almost any scale with discharge times ranging from several hours to a few days (For example there is a 1,800 MW pumped storage facility along the eastern shore of Lake Michigan (Ludington). The efficiency of pumped storage is in the 70% to 85% range.

There is over 90 GW of pumped storage in operation world wide, which is about 3 % of global generation capacity. Pumped storage plants are characterized by long construction times and high capital expenditure (>$1,800/kW). Pumped storage is the most widespread energy storage system in use on power networks.

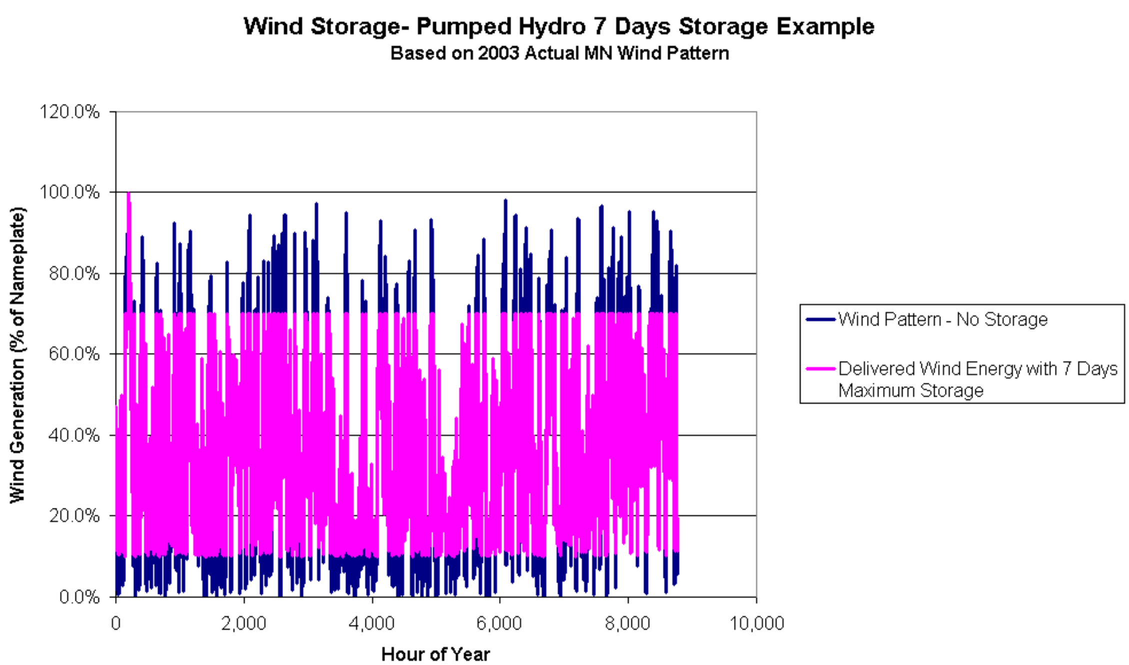
Figure E-2 below shows an annual wind energy pattern our system.

Figure E-2



A pumped storage facility could be used to moderate the amount of energy delivered as shown below.

Figure E-3



The cost for a 1,000 MW pumped storage system would likely approach $2 Billion. Such a facility could serve to alleviate a portion of the potential off-peak wind energy problem in 2020, but it would not eliminate it. The Company is concerned about how effective pumped storage would be relative to its cost. In addition, the Minnesota legislature has placed a moratorium on pumped storage facilities in Minnesota because most of the suitable sites for large-scale pumped storage in the state are located in environmentally sensitive areas along the St. Croix River, the Mississippi River, and the North Shore of Lake Superior.

Xcel Energy does have experience with pumped storage technology at its Cabin Creek facility in Colorado. Cabin Creek has historically been used to utilize off-peak coal-fired generation to pump up the upper reservoir for on-peak energy production. To date, it has not been used to moderate the delivery of wind energy.

Compressed Air Energy Storage ("CAES")

CAES is not a direct energy storage system. Off-peak electric energy is used to compress air that is stored under pressure in a salt cavern or underground mine. During on-peak periods, the compressed air is delivered as a combustion air source for a combustion turbine. Approximately 60% of the fuel consumed by a combustion turbine is used to compress its own intake air. A wind CAES system would utilize wind energy to displace 60% of the fuel consumed by the combustion turbine for compression. For salt cavern storage, it takes about 1.5 to 2 years to create such a cavern by dissolving salt. The following graphic shows a schematic of a CAES facility.

Figure E-4

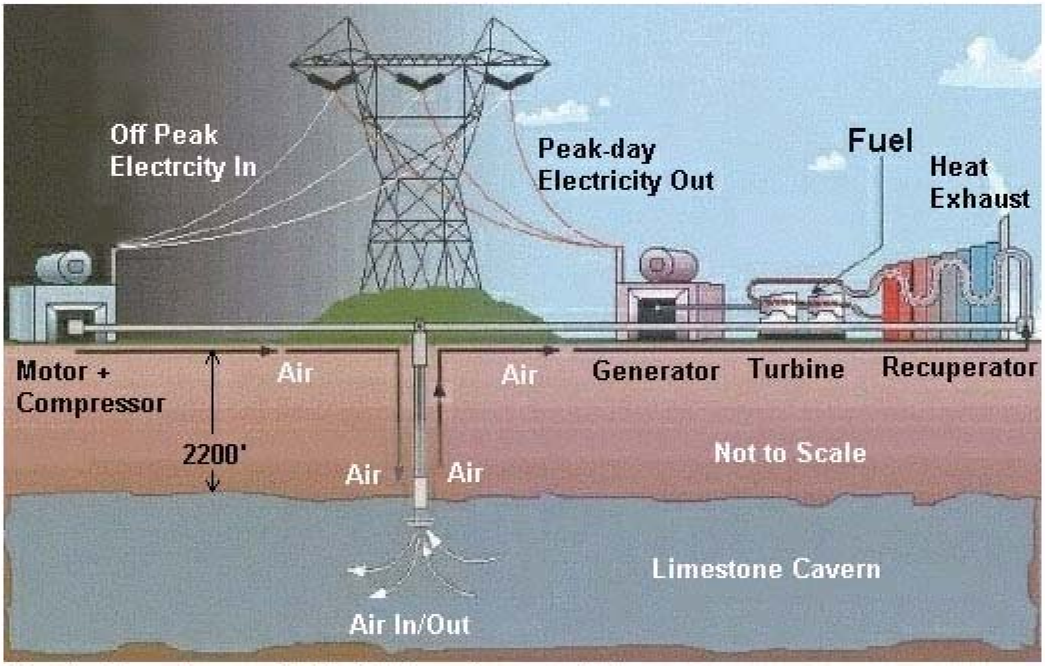


Photo Courtesy of CAES Development Company

The first commercial CAES project was a 290 MW unit built in Hundorf, Germany in 1978. The second commercial CAES was a 110 MW unit built in McIntosh, Alabama in 1991. The third commercial CAES, the largest ever, is a 2700 MW plant that is planned for construction in Norton, Ohio. This 9-unit plant will compress air to 1500 psi in an existing limestone mine some 2200 feet under ground. The current estimated cost of such a facility is in the range of $700/kW with energy conversion efficiency in the range of 80%.

Minnesota has neither suitable salt dome geology nor large-scale underground mines sufficient to support a 1,000 MW CAES facility. The Company is also concerned about the complexities entailed in operating such a facility.

Other Types of Batteries

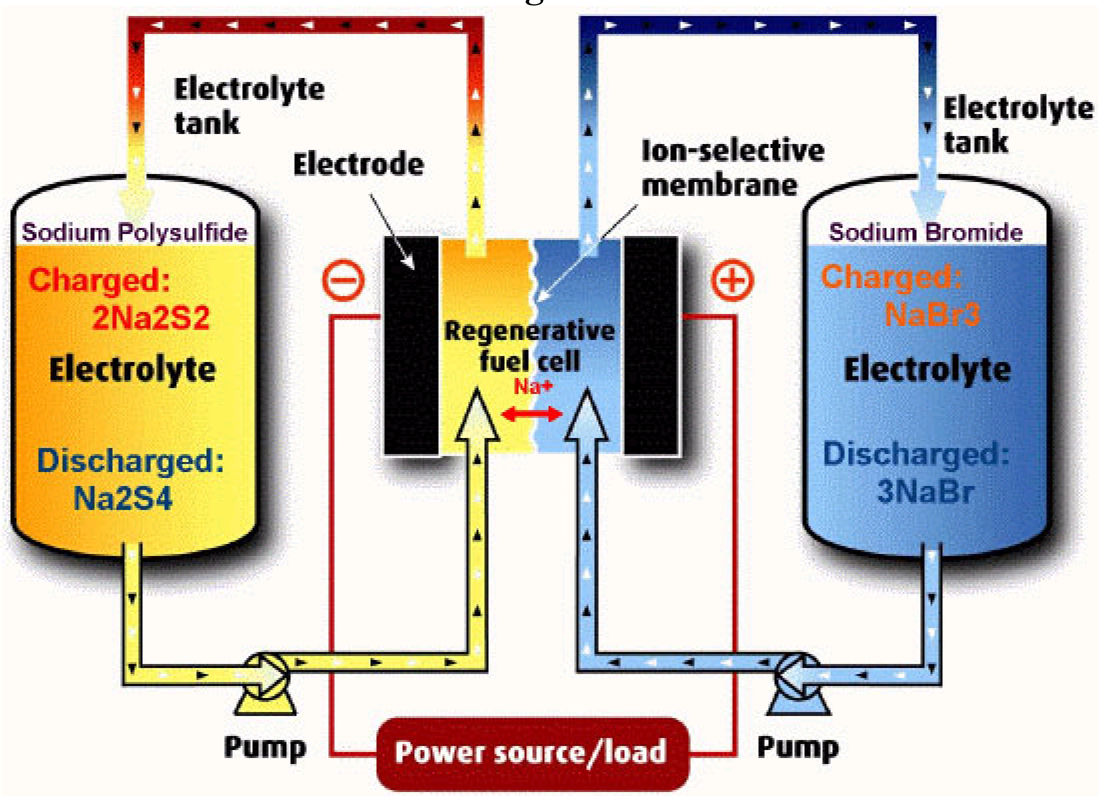
Lead-Acid Battery

Lead-acid battery technology is one of the oldest and most developed battery technologies. It is a low cost and popular storage choice for power quality, UPS and some spinning reserve applications. Its application for energy management, however, has been very limited due to its short cycle life. The amount of energy that a lead-acid battery can deliver is not fixed and depends on its rate of discharge. For those reasons, the Company does not consider lead-acid batteries to be suitable technology for wind energy storage

Polysulfide Bromide Battery

The Polysulfide Bromide battery ("PSB") is a regenerative fuel cell technology that provides a reversible electrochemical reaction between two salt solution electrolytes (sodium bromide and sodium polysulfide). PSB electrolytes are brought close together in the battery cells where they are separated by a polymer membrane that only allows positive sodium ions to go through, producing about 1.5 volts across the membrane. Cells are electrically connected in series and parallel to obtain the desired voltage and current levels. The net efficiency of this battery is about 75%. This battery works at room temperature. It has been verified in the laboratory and demonstrated at multi-kW scale in the UK. The Company is awaiting further development of this technology before it will be considered for a large-scale ($\geq$ 1 MW) demonstration project.

Figure E-5



Metal-Air Battery

Metal-air batteries are the most compact and, potentially, the least expensive batteries available. They are also environmentally benign. The main disadvantage, however, is that electrical recharging of these batteries is very difficult and inefficient. Although many manufacturers offer re-fuelable units where the consumed metal is mechanically replaced and processed separately, not many developers offer an electrically rechargeable battery. Rechargeable metal air batteries that are under development have a life of only a few hundred cycles and an efficiency of about 50%.

The anodes in these batteries are commonly available metals with high energy density like aluminum or zinc that release electrons when oxidized. The cathodes or air electrodes are often made of a porous carbon structure or a metal mesh covered with proper catalysts. The electrolytes are often a good

OH- ion conductor such as KOH. The electrolyte may be in liquid form or a solid polymer membrane saturated with KOH.

Figure E-6

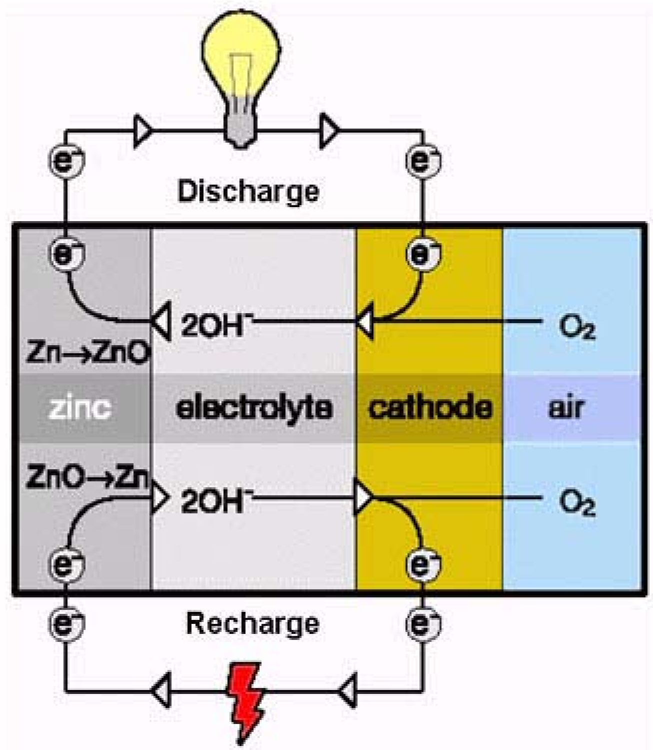


Photo Courtesy of EVonyx Inc.

While the Company is hopeful about the long-term prospects of utilizing this technology, the challenges associated with recharging them must be resolved before metal hydride batteries are considered for a large scale wind energy storage demonstration project.

Lithium-Ion Battery

The main advantages of Li-ion batteries, compared to other advanced batteries, are:

1. High energy density (300 - 400 kWh/m3, 130 kWh/ton)
2. High efficiency (near 100%)

3. Long cycle life (3,000 cycles @ 80% depth of discharge)

The cathode in these batteries is a lithiated metal oxide (LiCoO2, LiMO2, etc.) and the anode is made of graphitic carbon with a layer structure. The electrolyte is made up of lithium salts (such as LiPF6) 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 the combine with external electrons and are deposited between carbon layers as lithium atoms. This process is reversed during discharge.

While Li-ion batteries took over 50% of small portable market in a few years, there are some challenges for making large-scale Li-ion batteries. The main hurdle is the high cost (above $600/kWh).

Figure E-7

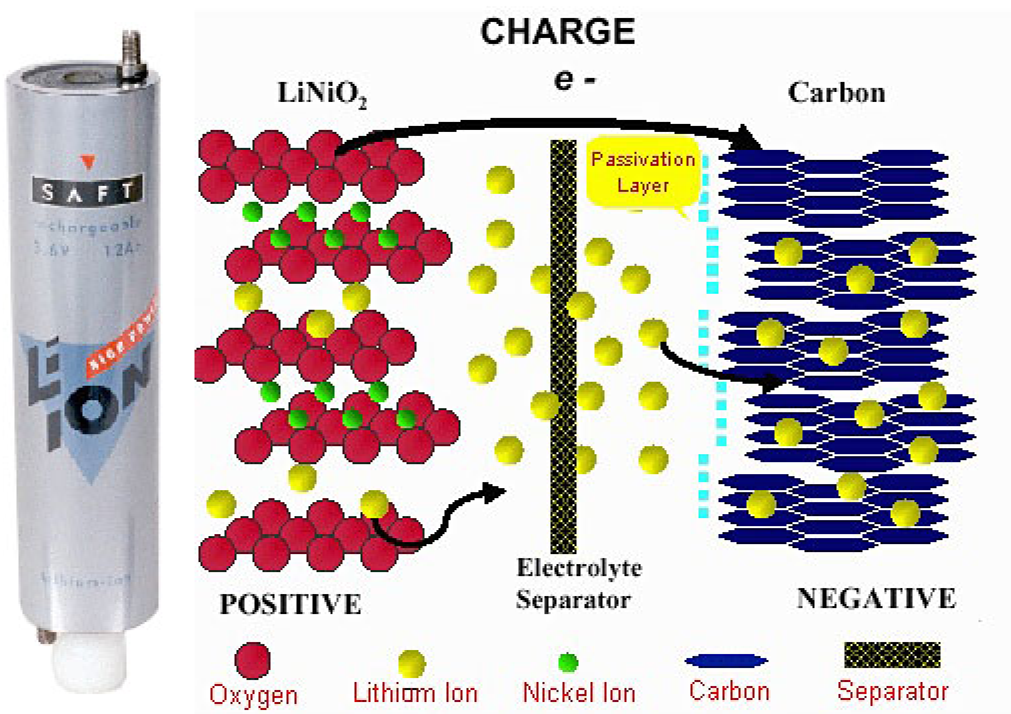


Photo Courtesy of SAFT America

Vanadium Redox Battery("VRB")

VRB store energy by employing vanadium redox couples (V2+/V3+ in the negative and V4+/V5+ in the positive half-cells). These are stored in mild sulfuric acid solutions (electrolytes).

During the charge/ discharge cycles, H+ ions are exchanged between the two electrolyte tanks through the hydrogen-ion permeable polymer membrane. The cell voltage is 1.4 -1.6 volts. The net efficiency of this battery can be as high as 85%. Like other flow batteries, the power and energy ratings of VRB are independent of each other.

VRB was pioneered in the Australian University of New South Wales in the early 1980's. The Australian Pinnacle VRB bought the basic patents in 1998 and licensed them to Sumitomo Electric Industries ("SEI") and VRB Power Systems. VRB storages up to 500kW, 10 hrs (5MWh) have been installed in Japan by SEI. VRBs have also been applied for power quality applications (3MW, 1.5 sec., SEI).

Figure E-8

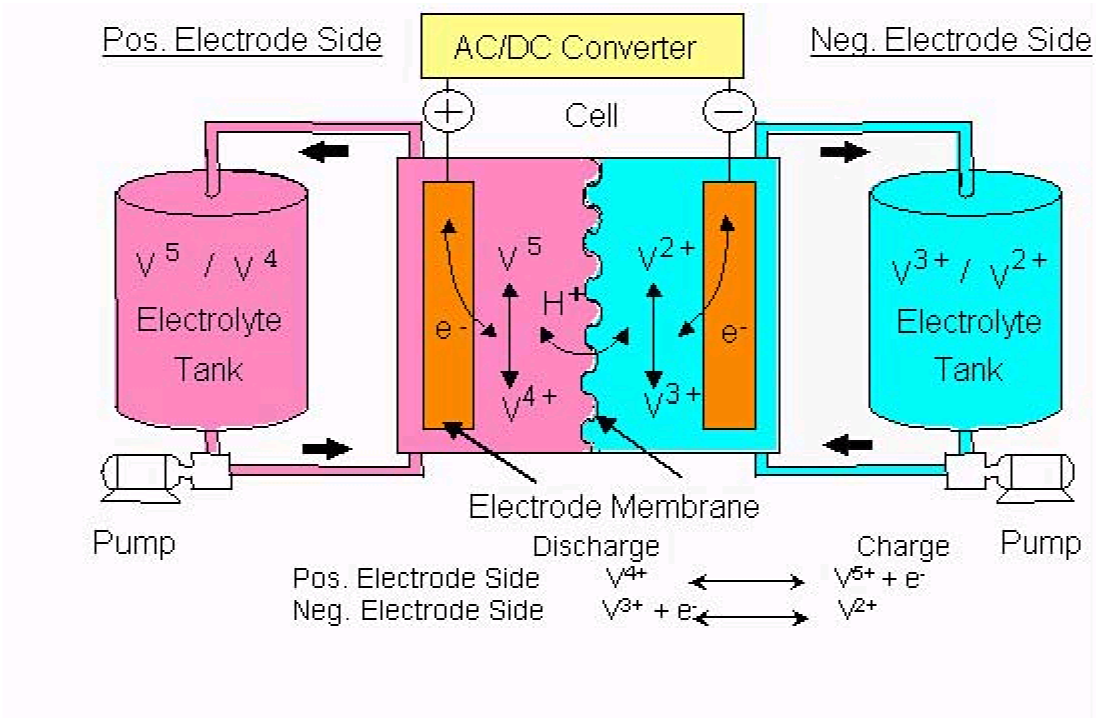


Photo Courtesy of Sumitomo Electric Industries, Ltd. (SEI) – Copyright 2001

The Company is awaiting further development of this battery technology before considering it for a large-scale demonstration project.

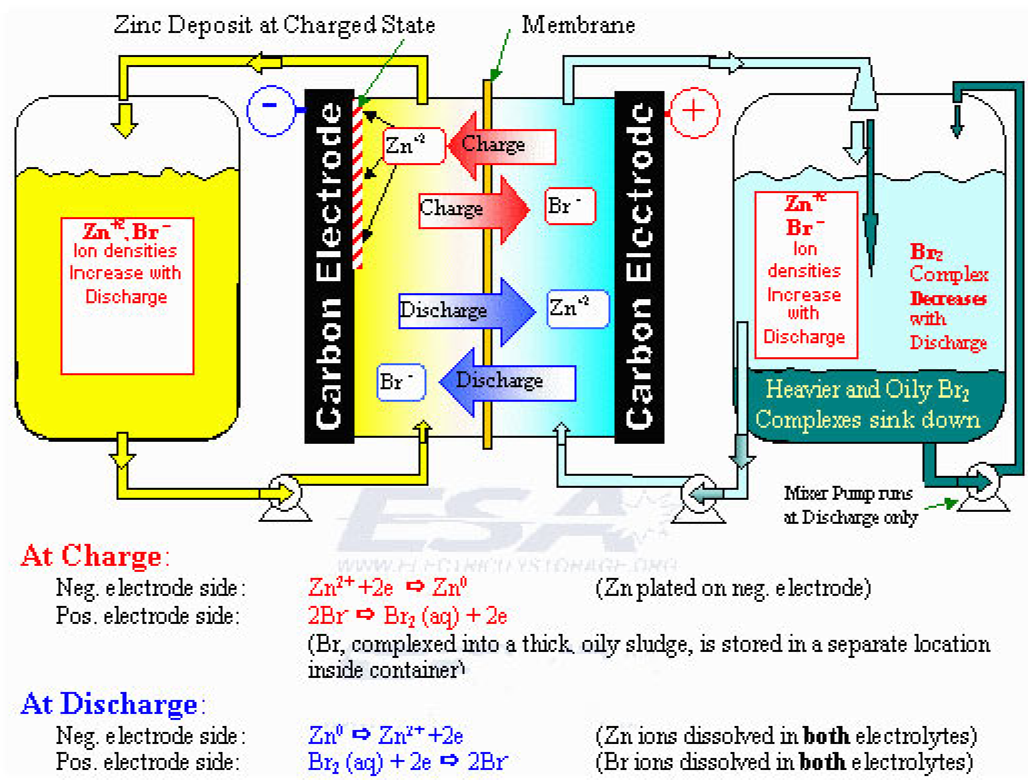
Zinc Bromine ("ZnBr") Battery

In each cell of a ZnBr battery, two different electrolytes flow past carbon-plastic composite electrodes in two compartments separated by a microporous polyolefin membrane.

During discharge, Zn and Br combine into zinc bromide, generating 1.8 volts across each cell. This will increase the Zn2+ and Br- ion density in both electrolyte tanks. During charge, metallic zinc will be deposited (plated) as a thin film on one side of the carbon-plastic composite electrode. Meanwhile, bromine evolves as a dilute solution on the other side of the membrane, reacting with other agents (organic amines) to make thick bromine oil that sinks down to the bottom of the electrolytic tank. It is allowed to mix with the rest of the electrolyte during discharge. The net efficiency of this battery is about 75%.

The ZnBr battery was developed by Exxon in the early 1970's. Over the years, many multi-kWh ZnBr batteries have been built and tested. Meidisha demonstrated a 1MW/4MWh ZnBr battery in 1991 at Kyushu Electric Power Company. Some multi-kWh units are now available pre-assembled, complete with plumbing and power electronics.

Figure E-9



The Company considers this technology better suited to power quality management applications than for energy storage.

Conclusions

Given the potential magnitude of wind energy storage that would be needed for our, the Company believes that large scale technologies, such as pumped storage and compressed air energy storage, are either very difficult to permit or require unique geology not present in near Minnesota's best wind resources or near the Company's predominant load in the Twin Cities metro area. Scalable storage in the form of advanced technology batteries or fuel cells as well as chemical conversion technologies hold promise, but need to be demonstrated on a smaller scale to be both operationally and economically feasible before scaling up to the potential magnitude of wind energy storage capability needed on our system. The Company will report results of its current experiments as well as any further experiments it undertakes in its next Resource Plan filing in 2009 or 2010.