BATTERY STORAGE SYSTEMS IN ELECTRIC POWER SYSTEMS

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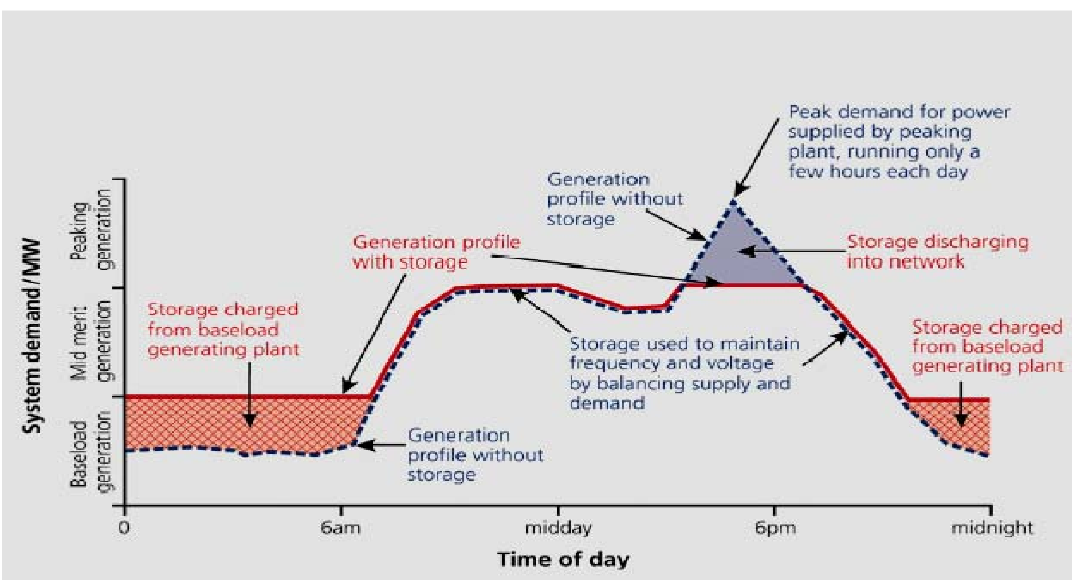
1. INTRODUCTION

Energy storage has been the most challenging and complex issue of the industry whether it is the electric utilities or for industrial applications. The new and evolving applications are seen in the areas of electric and electric hybrid vehicles, electric utility storage, portable electronics and storage of electric energy produced by renewables like solar or wind generators. The constant need for efficient energy storage has seen the emerging new technologies which promise reliability, productivity and the use of renewables. Energy storage can balance the fluctuations in supply and meet the ever growing demand of electricity. For short duration requirements battery storage can bring about frequency control and stability and for longer duration requirements they can bring about energy management or reserves. Storage also can be used to complement primary generation as they can be used to produce energy during off peak periods and this energy produced can be stored as reserve power as shown by the following graph. Storage can play a multi-function role in the electric supply network to manage the resources effectively.

- Energy storage can bring about a reduction in operating costs or capital expenditures when used as a generation resource in the utility sector.
- When used with renewable resources, energy storage can increase their usability of photovoltaic and wind generated electricity by making this generation coincident with peak load demand. Energy storage may facilitate the inclusion of wind and solar energy into the electric grid.
- Energy storage can increase the existing transmission and distribution equipment and eliminate the need for expensive T & D additions. Energy storage can be used to reduce the load on peaking transmission lines. Therefore summing up some of the T & D benefits are (a) deferral of the construction of new transmission lines, transformers, capacitor banks, substations or their subsequent upgrade (b) transmission line stability preventing possible system collapse (c) increasing power quality of the service which would result in protection of customer equipment.
- Energy storage has been used in stand-alone application since a long time, where it serves as uninterruptible power supply (UPS) unit. UPS units are basically used for back-up power whereas energy storage today can serve a number of on-line applications.



The graph explains that the system demand can be handled efficiently if storage is incorporated into the electrical network. As shown the storage is charged from the baseload generating plant during the early hours of the day when the demand is low. And then as the demand rises during the day the generating plants belonging to mid merit category, account for the demand. And during the peak demand time if storage is taken into account then the demand can be supplied by the peaking plant which runs only for few hours of the day decreasing the total cost of operating such a storage incorporated system. Thus we see that when the generation profile with storage is taken, there is a much controlled demand graph as storage takes care of the load leveling and then it is charged again at the end of the day from the baseload generating plant.

2. ELECTRIC STORAGE TECHNOLOGIES

A number of electric storage technologies have been developed which serve various electric applications, including:

- Pumped Hydropower
- Compressed air energy storage (CAES)
- Batteries
- Flywheels
- Superconducting magnetic energy storage (SMES)
- Super capacitors
- Hydrogen Storage

2.1 Pumped Hydropower:

Pumped hydro has been around as an electric storage technology since 1929, making it the oldest used technology.

Operation:
Conventional pumped hydro facilities consist of two reservoirs, each of which is built at two different levels. A body of water at the higher elevation represents potential or "stored" energy. Electrical energy is produced when water is released from this reservoir to the lower reservoir while causing the water to flow through hydraulic turbines which generate electric power as high as 1000 MW. Within last ten years the advanced pumped storage (APS) technology has been introduced to increase efficiency, speed and reliability.

Example:
A seawater pumped hydro plant was first built in Japan in 1999 (Yanbaru, 30 MW). There is over 90 GW of pumped storage in operation world wide, which is about 3 % of global generation capacity.

2.2 Compressed Air Energy Storage (CAES):

CAES is an attractive energy storage technology for large, bulk storage.

Operation:
CAES systems store energy by compressing air within an air reservoir using a compressor powered by low cost electric energy. During charging the plant's generator operates in reverse – as a motor – to send compressed air into the reservoir. When the plant discharges, it uses the compressed air to operate the combustion turbine generator. This method is more efficient because natural gas is burned in this process as compared to a conventional turbine plant as the CAES plant uses all of its mechanical energy to generate electricity.
An important performance parameter for a CAES system is the charging ratio, which is defined as the ratio of the electrical energy required to charge the system versus the electrical energy generated during discharge (the number of kilowatt hour (kWh) input in charging to produce 1 kWh output).

Example:
In 1991, the first U.S. CAES facility was built in McIntosh, Alabama, by the Alabama Electric Cooperative and EPRI, and has a capacity of 110 MW.

2.3 Flywheels:

Operation:
A flywheel storage device consists of a flywheel that spins at a very high velocity and an integrated electrical apparatus that can operate either as a motor to turn the flywheel and store energy or as a generator to produce electrical power on demand using the energy stored in the flywheel. The use of magnetic bearings and a vacuum chamber helps reduce energy losses. Flywheels have been proposed to improve the range, performance and energy efficiency of electric vehicles. Development of flywheels for utilities has been focused on power quality applications.

Example:
While high-power flywheels are developed and deployed for aerospace and UPS applications, there is an effort, pioneered by Beacon Power, to optimize low cost commercial flywheel designs for long duration operation (up to several hours). 2kW / 6kWh systems are in telecom service today.

2.4 Advanced Electrochemical Capacitors:

Operation:
An electrochemical capacitor has components related to both a battery and a capacitor. Consequently, cell voltage is limited to a few volts. Specifically, the charge is stored by ions as in a battery. But, as in a conventional capacitor, no chemical reaction takes place in energy delivery.
An electrochemical capacitor consists of two oppositely charged electrodes, a separator, electrolyte and current collectors.

Example:
Presently, very small super capacitors in the range of seven to ten watts are widely available commercially for consumer power quality applications and are commonly found in household electrical devices. Development of larger-scale capacitors has been focused on electric vehicles. Currently, small-scale power quality (<250 kW) is considered to be the most promising utility use for advanced capacitors.

Technology	Installed (U.S total)	Facility Size Range	Potential/Actual Applications	Commercially Available	Estimated Costs
Pumped Hydro	22 GW at 150 facilities in 19 states	Up to 2.1 GW	Electricity * Load Leveling * Spinning Reserve	Yes	500-1600$/kW
CAES	110 MW in Alabama	25 MW to 350 MW	Electricity * Peak Shaving * T&D Applications * Spinning Reserve	Yes	350-500 $/kW
Batteries	More than 70 MW installed by utilities in 10 states	From 100W to 20 MW	Electricity * Spinning Reserve * Integration with Renewables * T&D Applications * Power Quality * Peak Shaving	Yes (Flooded Lead-Acid, VRLA) No (Zinc/Bromine, Lithium)	750-1000 S/kW (20-40MW, 2 hrs) 500-600 $/kW (20-40MW, 0.5 hr) 400-600 $/kW (2 MW, 10-20 sec)
Flywheels	1-2 demo facilities, no commercial facilities	kW-scale	Electricity * Power Quality	Yes (steel, low rpm)	Advanced: 6000 $/kW (~1kW) 3000 $/kW (~kW)
SMES	5 facilities with approx. 30 MW in 5 states	From 1-10 MW (micro-SMES) to 10-100 MW	Electricity * T&D Applications * Power Quality	Yes (micro-SMES) No (larger units)	1000 $/kW

Having discussed all the different types of energy storage, we compare the different technologies in the table below:

3. BATTERY ENERGY STORAGE SYSTEMS

In recent years much of the focus on the development of electric storage technology has been on batter storage which is the main emphasis of this paper. There is a wide variety of battery types serving various purposes which would be examined in this paper.

In a chemical battery, charging causes reactions in electrochemical compounds to store energy from a generator in a chemical form. Upon demand, reverse chemical reactions cause electricity to flow out of the battery and back to the grid. The first commercially available battery was the flooded lead-acid battery which was used for fixed, centralized applications. The valve-regulated lead-acid (VRLA) battery is the latest commercially available option. The VRLA battery is low-maintenance, spill- and leak-proof, and relatively compact. Zinc/bromine is a newer battery storage technology that has not yet reached the commercial market. Other lithium-based batteries are under development. Batteries are manufactured in a wide variety of capacities ranging from less than 100 watts to modular configurations of several megawatts. As a result, batteries can be used for various utility applications in the areas of generation, T&D, and customer service. Batteries currently have the widest range of applications as compared to other energy storage technologies. The type and the number of battery storage applications are constantly expanding mainly in the areas of electric and electric hybrid vehicles, electric utility energy storage, portable electronics, and storage of electric energy produced by renewable resources such as wind and solar generators.

They are also used for a variety of applications such as: power quality assurance, transmission and distribution (T&D) facility deferral, voltage regulation, spinning reserve, load leveling, peak shaving, and integration with renewable energy generation plants. Battery systems appear to offer the most benefits for utilities when providing power management support and when responding to instant voltage spikes or sags and outages.

Operation

Electric batteries are devices that store electric energy in electrochemical form and deliver direct (dc) electricity. Electrode plates, typically consisting of chemically reactive materials, are placed in an electrolyte which facilitates transfer of ions within the battery. The negative electrode, or anode, "gives up" electrons during discharge via the oxidation part of the oxidation-reduction electrochemical process. Those electrons flow through the electric load connected to the battery, giving up energy. Electrons are then transported to the positive electrode, or cathode, for electrochemical reduction. The process is reversed during charging. Battery systems consist of cells, which have a characteristic operating voltage and maximum current capability, configured in various series/parallel arrays to create the desired voltage and current. Typically a BESS consists of a power conditioning system (PCS) that processes electricity from the battery and makes it suitable for alternating current (ac) loads. This includes (a) adjusting current and voltage to maximize power output, (b) converting DC power to AC power, (c) matching the converted AC electricity to a utility's AC electrical network, and (d) halting current flow from the system into the grid during utility outages to safeguard utility personnel. The conversion from DC to AC power in the PCS is achieved by an inverter, which is a set of electronic switches that change DC voltage from battery to AC voltage in order to serve an AC load.

3.1 Available Types of Battery Storage

Until recently, the only battery technology that was economically feasible is the lead acid battery. Improved valve regulated lead-acid (VRLA) batteries are now emerging in utility systems. Advanced batteries (such as lithium ion and zinc/bromide) are being developed and are at different levels of size and readiness for utility operation.
Following are the different kinds of battery available in the market today:

A. Lead-Acid Battery

Lead acid batteries are marginally economic but they have substantial space and maintenance requirements. They also have a shorter life, which decreases rapidly if battery is discharged below 30%. This results in the reduction of energy density amounting to increased capital costs. They are commonly installed in uninterruptible power supply (UPS) systems as well as in renewable and distributed power systems. The largest one installed is a 40 MWh system in Chino, California.
They have several key limitations: (a) they require relatively frequent maintenance to replace water lost in operation, (b) they are relatively expensive compared to conventional options with limited reduction in cost expected, and (c) because of their use of lead, they are heavy, reducing their portability and increasing construction costs. The strengths of flooded lead-acid batteries center around their relatively long life span, durability, and the commercial availability of the technology.

B. Valve Regulated Lead Acid Battery (VRLA)

VRLAs use the same basic electrochemical technology as flooded lead-acid batteries, but these batteries are closed with a pressure regulating valve, so that they are essentially sealed. In addition, the acid electrolyte is immobilized. This eliminates the need to add water to the cells to keep the electrolyte functioning properly, or to mix the electrolyte to prevent stratification. The oxygen recombination and the valves of VRLAs prevent the venting of hydrogen and oxygen gases and the ingress of air into the cells. The battery subsystem may need to be replaced more frequently than with the flooded lead-acid battery, increasing the levelized cost of the system. The major advantages of VRLAs over flooded lead-acid cells are: a) the dramatic reduction in the maintenance that is necessary to keep the battery in operation, and b) the battery cells can be packaged more tightly because of the sealed construction and immobilized electrolyte, reducing the footprint and weight of the battery. The disadvantages of VRLAs are that they are less robust than flooded lead-acid batteries, and they are more costly and shorter-lived. VRLAs are perceived as being maintenance-free and safe and have become popular for standby power supplies in telecommunications applications and for uninterruptible power supplies in situations where special rooms cannot be set aside for the batteries.

3.2 Use in UPS Systems

Battery applications are predominantly used for reserve power in uninterruptible power supply systems (UPS). Generally flooded cell batteries, sealed-cell batteries and flywheels are the number one choice for UPS today. Flywheels are useful for certain space-critical requirements but they cost much more than other batteries and are subject to bearing reliability and environmental issues due to high spin issues. Flooded cell batteries are the most reliable choice as they exhibit better mean time between failure (MTBF) levels as compared to either flywheels or valve regulated lead acid (VRLA) batteries. But flooded cell batteries are the most expensive kind either as first cost or on installed cost basis. According to one paper, more than 90% of installed UPS systems with power levels ranging up to 500 kVA or more rely on VRLA batteries.
In contrast to other types of UPS energy storage, VRLA battery systems are relied upon primarily due to (a) the dramatic reduction in the maintenance that is necessary to keep the battery in operation, (b) the battery cells can be packaged more tightly because of the sealed construction and immobilized electrolyte, reducing the footprint and the weight of the battery. Heat is perhaps the worst enemy of stationary lead-acid batteries. Depending on manufacturer and product, expected life of all lead-acid batteries will be cut in half for every 10º to 15ºF rise in temperature over recommended usage, which is usually 77ºF. This is because excessive heat in VRLAs leads to dry-out and open circuit failure. Next on the list of factors are cycling or battery discharge events. Most UPS systems cycle batteries not just during outages, but also for changes in load levels, as well as large dips in input voltage. In fact, many battery companies now limit warranties based upon the number and duration of these discharge cycles. Charge voltage, current and duration also affects VRLA reliability. Most sealed VRLA batteries currently being manufactured and bid for UPS applications in the United States have a five-year design or target life. It could be longer with ambient reduction, cycling and depending on the manufacturer, or it could be shortened by the factors already discussed.

Good UPS maintenance will include battery voltage, resistance or impedance testing, some of which is built right in to modern UPS charging and monitoring circuits, as well as visual inspection, cleaning and later on, retorquing or infrared scanning connections. Overall UPS system reliability is more dependent upon the DC component of the system than any other element. VRLA batteries will remain the DC component of choice for most UPS systems for many years to come. By integrating good system and service design, high levels of VRLA battery reliability can be achieved.

A. Lithium ion Battery (Li-Ion)

The main advantages of Li-ion batteries, compared to other advanced batteries, are: (a) High energy density (300 - 400 kWh/m3, 130 kWh/ton) (b) High efficiency (near 100%) (c)Long cycle life (3,000 cycles @ 80% depth of discharge). The cathode in these batteries is a lithiated metal oxide ($LiCoO_2$, $LiMO_2$, etc.) and the anode is made of graphitic carbon with a layer structure. The electrolyte is made up of lithium salts (such as $LiPF_6$) 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) due to special packaging and internal overcharge protection circuits. Several companies are working to reduce the manufacturing cost of Li-ion batteries to capture large energy markets.

B. Vanadium Redox Flow Battery (VRB)

VRB stores energy by employing vanadium redox couples (V^{2+}/V^{3+} in the negative and V^{4+}/V^{5+} 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 (UNSW) in early 1980's. 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).

C. Zinc Bromine Flow Battery (ZnBr)

In each cell of a ZnBr battery, two different electrolytes flow past carbon-plastic composite electrodes in two compartments separated by a micro porous polyolefin membrane. During discharge, Zn and Br combine into zinc bromide, generating 1.8 volts across each cell. This will increase the Zn^{2+} 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.

D. Sodium Sulfur Battery (NaS)

A NaS battery consists of liquid (molten) sulfur at the positive electrode and liquid (molten) sodium at the negative electrode as active materials separated by a solid beta alumina ceramic electrolyte. The electrolyte allows only the positive sodium ions to go through it and combine with the sulfur to form sodium polysulfides. During discharge, as positive Na^+ ions flow through the electrolyte and electrons flow in the external circuit of the battery producing about 2 volts. This process is reversible as charging causes sodium polysulfides to release the positive sodium ions back through the electrolyte to recombine as elemental sodium. The battery is kept at about 300 degrees C to allow this process. NaS battery cells are efficient (about 89%) and have a pulse power capability over six times their continuous rating (for 30 seconds). This attribute enables the NaS battery to be economically used in combined power quality and peak shaving applications. 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. The largest NaS installation is a 6MW, 8h unit for Tokyo Electric Power company.

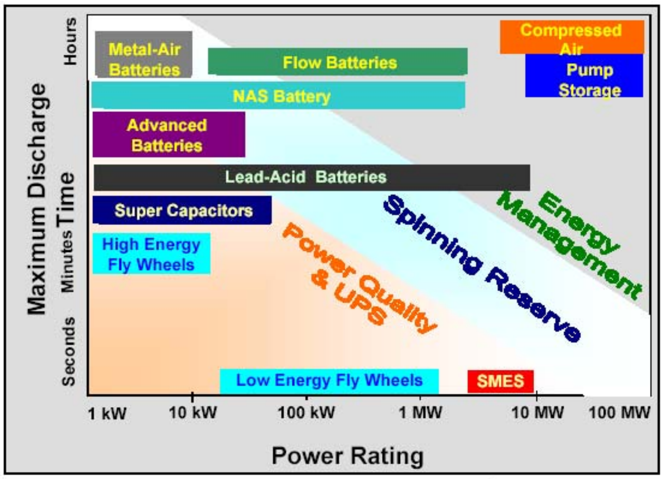
E. Metal-Air Battery

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 refuelable 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 efficiency 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. While the high energy density and low cost of metal-air batteries may make them ideal for many primary battery applications, the electrical rechargeability feature of these batteries needs to be developed further before they can compete with other rechargeable battery technologies.

F. Polysulfide Bromide Flow Battery (PSB)

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.

Regenesys Technologies is building a 120 MWh, 15 MW energy storage plant at Innogy's Little Barford Power Station in the UK. Tennessee Valley Authority (TVA) is also planning to build a 12 MW, 120 MWh unit in Mississippi (USA) to be operational in late 2004.



Electricity Storage Association

Thus having talked about different battery storage technologies here we compare them. From the above graph shown, we come to the following conclusions:

- ✓ For energy storage involving greater capacity systems, generally pumped storage and CAES storage systems are used whereas for lower storage applications, High Energy Fly Wheels, Super capacitors and batteries are used.
- ✓ For mid capacity applications generally flow batteries, lead-acid batteries and NaS batteries are used.
- ✓ CAES and Pumped Hydro are more costly as compared to other technologies but they also served larger load applications.

4. PLANT CONSTRUCTION

A BESS facility is typically much smaller than a PHS or CAES facility, largely because there are fewer geological requirements, economy of scale factors, and because BESS facilities can be placed close to the load. Site buildings are dependent on the type of battery: lead-acid batteries are being housed in an enclosed structure, while flow batteries may use separate external storage tanks, depending on the application. The Power Conditioning System (PCS), which consists of rectifiers and DC-AC inverters, requires cooling under high load conditions. The presence of potentially hazardous liquid electrolytes may restrict siting, and require additional monitoring and containment equipment. Figure below shows the basic features of a large 15 MW, 120 MWh flow battery system, including external electrolyte tanks, and an enclosed structure that contains the stack and PCS system. Another project has been set up in Metlakatia, Alaska having a capacity of 1.0 MW 1.4MWh using GNB Absolyte II VRLA using G.E Power Conditioning System. It had a system cost of $2.2M US in 1997 with an expected payoff in 3 years.

4.1 Capital Equipment

A complete BESS system consists of PCS, battery stacks, electrolyte tanks and pumps, as well as electrolyte materials. The battery components vary widely depending on type, but the PCS and balance of plant are similar, and will be assessed equally for both types. In order to assess the facilities equally, a unit lifetime of 15 years is assumed. During this time, the lead-acid batteries will require replacement. Virgin materials are assumed for the manufacture of all components, except the second set of lead-acid batteries, where a 99% secondary lead source is assumed, representing a closed-loop recycling process.

A substantial advantage of BESS is the ability to place the unit at or near the point of use. There are no geologic requirements, and since there are no operation-related emissions, batteries can be placed near or in occupied buildings. BESS units may be placed at substations for local voltage support, and may also provide additional economic benefits such as transmission and delivery (T&D) deferral and increased system reliability. This geographical benefit translates to substantially reduced transmissions losses associated with BESS use as compared with CAES or PHS. Placement at substations reduces the incremental BESS transmission distance to near zero. While the round trip electrical conversion efficiency for a battery cell can be substantially higher than PHS system (in excess of 90% for vanadium) additional loads substantially decrease the net efficiency of BESS systems. Flow batteries require fluid pumps, which decrease overall efficiency by approximately 3%, and active cooling requirements result in additional losses. Unlike PHS or CAES, batteries store and produce direct current, which require AC-DC converters. These solid state devices have improved in both efficiency and cost, but are still more expensive and less efficient than transformers of equivalent power. Typical losses associated with roundtrip AC-AC conversion are at least 4%, and can be significantly higher depending on loading conditions.

4.2 Operation & Maintenance Requirements

There are no major consumables associated with BESS operation, so additional energy requirements are derived primarily from system maintenance and repair. Energy and emissions requirements are calculated using EIO methods based on estimated annual maintenance costs. Costs for lead-acid batteries are generally available, while O&M costs for flow-batteries is more difficult to assess due to a lack of an installed base. Flow batteries are expected to require substantially less maintenance then lead-acid batteries, primarily electrolyte evaluation, and periodic replacement of pumps and stack components. Large scale advanced BESS systems do not require full-time manual supervision.

5. BATTERY STORAGE FOR RENEWABLE ENERGY SYSTEMS

A few battery energy storage systems are currently being demonstrated, some with U.S. DOE Energy Storage Systems (ESS) Program funding. Crescent Electric Membership Cooperative (CEMC) has been using a 500 kW lead-acid battery energy storage system for peak shaving purposes since 1987. CEMC has been able to significantly reduce the demand charges paid to its generation and transmission cooperative, North Carolina Electric Membership Cooperative. Niagara Mohawk funded an investigation into peak load reduction with PV and buffer battery storage. The utility and the Empire State Electric Energy Research Corporation installed a 13 kW (AC) PV system on an energy-efficient office building in Albany, NY in 1990. The PV system operated as designed, but because afternoon clouds were reducing the PV system's effect on peak demand somewhat, Niagara Mohawk added a 21 kW/1-hour battery storage system in July 1993. The PV/battery prototype had the two systems operate in parallel, with off-peak grid power used to recharge the battery.

EPRI, Sandia National Laboratories, and the Salt River Project electric utility installed a 2.4 kW PV array and 25.2 kWh battery in an experimental residence owned by the utility. The system was designed to discharge the PV generated electricity stored in the batteries to match specific three-hour peak loads. The PV/battery system has operated continually and reliably since its installation in August 1995. No repairs or homeowner involvement has been needed. The only maintenance performed was periodic watering of the battery cells and manually changing the dispatch schedule each season.

The Yuma Proving Ground in Arizona has a grid-tied 441 kW PV system with 5.6 MWh of lead-acid batteries. During the summer peak season, the system can deliver 825 kW to the grid to help reduce peak demand. The system can also operate stand-alone in the event of an extended outage.

6. CONCLUSIONS

Critical environmental aspects have been identified and quantified for established and emerging battery systems. The environmental impact of a battery system is mainly influenced by its application and conditions of use and the choice of battery technology should be assessed for each specific application. In applications where batteries are difficult to collect at the end of their life, material flows and dissipative losses of toxic metals are of main concern. Energy requirements during production and usage are important for battery systems where the material losses throughout the battery life cycle are low. For portable batteries, dissipative *losses of toxic metals* from incineration and landfills are of environmental concern.

- Measures of the performance of the different battery technologies used in a PV-battery system were obtained by the energy return factor and the overall battery efficiency. With a battery storage capacity three times higher than the daily energy output, the energy return factor for the PV-battery system ranged from 0.64 to 12 for the different cases. This means that 8.1-156% of the energy output is required to produce the PV-battery system. If the value of the energy return factor is less than one, the indirect energy used to produce and replace the device is greater than the energy output. In this case the device works similar to that of a non-rechargeable battery, simply moving energy from one place to another. If PV-battery systems are to contribute to a renewable energy supply, it is important to improve the energy efficiency of all their components. For a PV–battery system with a service life of 30 years, the energy payback time is 2.4-46 years, depending on the battery technology and operating conditions. The energy payback time is 1.6-3.0 years for the PV array and 0.55-43 years for the battery, showing the energy related significance of batteries in PV-battery systems. Some of the emerging technologies studied (e.g. Li-ion, NaS) exhibit performance suitable for use in PV-battery systems, resulting in higher energy return factors and overall battery efficiencies than for the established battery technologies.
- The influence of different parameters on environmental impact and energy flows of battery systems are crucial.
- Product characteristics of portable batteries, that are related to losses of metals, are the small size of each battery unit, the large number of battery owners, low concentration of economic value and type of application. Portable batteries also have a short effective service life, which increase the turnover of materials.
- Material flows of industrial batteries are easier to control due to the limited number of owners and the large size, which reduces the risk of loss and inappropriate disposal. To decrease losses of metals to the environment, collection of spent products is more important than the technical efficiency of recycling processes. NiCd battery recycling is energy efficient, even at very long transportation distances, at collection rates of 10-85%.

Important parameters affecting *energy flows* in battery systems are the battery charge discharge efficiency, the type of cycling regime, the battery service life and the energy requirements for battery production.

- In cases where the focus is on the efficient use of fossil fuels, and electricity generated by solar energy can be considered as a free energy source, a high energy return factor is important.
- Sensitivity analysis showed that the charge-discharge efficiency is the battery parameter

with the highest influence on the energy return factor and is most important for lithium-ion, sodium-sulphur, polysulphide-bromide, vanadium-redox and zinc-bromine batteries.

- Service life, energy density and energy requirements for battery production are of equal importance for nickel-cadmium, nickel-metal hydride and lead-acid batteries.
- The overall battery efficiency provides a measure of the efficiency of a closed renewable system, where renewable energy has to be used as efficiently as possible. The battery charge-discharge efficiency has the greatest influence on the overall efficiency. Lithium-ion and sodium-sulphur are emerging battery technologies with favourable characteristics in this respect.
- The *environmental impact* of battery systems can be reduced by matching operating conditions and battery characteristics in a life cycle perspective. To decrease the environmental impact of battery systems, the development of battery technologies should aim at the recycling of materials, increased service lives and higher energy densities. To decrease the environmental impact arising from the use of *metals* in battery systems, metals with relatively *high natural occurrence* should be used, and regulations implemented to *decrease the need for virgin metals*.
- To increase the overall *energy efficiencies* of battery systems, the development of battery technologies should aim at *higher charge-discharge efficiencies* and more *efficient production* and *transport* of batteries.
-*Energy analysis* can be used to assess the net energy output of renewable energy systems requiring energy storage in batteries. The energy return factor and the overall battery efficiency can be useful indicators of the battery system requirements of fossil fuels and electricity from a closed renewable system, respectively.
- Battery energy storage systems are a disruptive technology altering power system planning and operation.
- The electric industry can look forward to install generating capacity to meet average demand and therefore modulate on storage.
- And thus effectively run generation plant at optimum conditions for efficiency and emissions.

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