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ELECTRIC UTILITY APPLICATIONS OF HYDROGEN ENERGY STORAGE SYSTEMS

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EXECUTIVE SUMMARY

This report analyzes the various applications of energy storage systems for electric utility applications, and appraises the suitability of different storage technologies to meet those application needs. Load leveling and 'firming' of intermittent renewable resources are two applications best suited for hydrogen energy storage systems due to the need for long duration storage and frequent cycling in these applications. After analyzing hydrogen, battery, flywheel, superconducting magnets, compressed air, and pumped-hydro energy storage systems and their applications, the analysis suggests that the battery energy storage (BES) system is the closest competitor to hydrogen energy storage (HES) system for the two identified applications.

BES systems enjoy the modularity and sitting advantages like HES systems. The analysis shows that HES systems are cost-effective for applications that require storage durations of greater than twelve hours, while BES systems are favored for durations less twelve hours.

In order to establish benchmarks to develop HES systems, the capital cost data of commercial scale BES systems were investigated. This cost data can provide a benchmark against which HES systems must be measured if they are to be commercially viable.

1.0 INTRODUCTION

Electrolysis of water is one method for producing hydrogen. Hydrogen also reacts with the oxygen in air within a fuel cell to produce electricity. Hydrogen therefore has the potential of being an effective storage medium for electricity. Low cost off-peak electricity can be used to produce hydrogen. The hydrogen can then be stored and utilized in a fuel cell to produce electricity during periods of peak demand. Recent studies[1] indicate that significant price differential exist between off-peak and on-peak electricity, to seriously consider the feasibility of using hydrogen as a means of storing electrical energy.

Pumped-hydro systems are capable of "storing electricity for long duration." Currently approximately 20 GW of pumped-hydro storage capacity is available nationally[2]. Cost-effectiveness of pumped hydro systems are very site-specific, and current projections are that there will only be very limited increases in such systems nationally. Compressed Air Energy Storage (CAES) is another storage system that was developed with Electric Power Research Institute (EPRI) and U.S. Department of Energy (DOE) support. A commercial scale system was installed at Alabama Electric Cooperative. This system is capable of storing approximately 2600 MWh and has been in commercial operation since 1996[3]. Cost-effectiveness of CAES systems are also site-specific. The site-specific nature, coupled with very limited demand for long-duration electric energy storage over the last decade, has limited the market entry of CAES in the electric utility sector.

The recent emphasis on deregulation and the concomitant competitive pressures have encouraged the electric utility industry to examine innovative distributed generation and storage concepts in more detail. Many new applications of storage that involves better asset utilization have been identified. Several demonstration projects as well as a few commercial installation of energy storage (ES) systems have resulted.

The emergence of intermittent renewable generation for off-grid and grid-connected distributed generation applications have also provided impetus for installing cost-effective energy storage systems. ES systems "firm up" the intermittent renewable generation resources thus adding value.

This report examines the capital cost associated with various energy storage systems that have been installed for electric utility application. The storage systems considered in this study are Battery Energy Storage (BES), Superconducting Magnetic Energy Storage (SMES) and Flywheel Energy Storage (FES). The report also projects the cost reductions that may be anticipated as these technologies come down the learning curve. This data will serve as a base-line for comparing the cost-effectiveness of hydrogen energy storage (HES) systems in the electric utility sector. Since pumped hydro or CAES is not particularly suitable for distributed storage, they are not considered in this report.

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[1] Electrolytic Hydrogen Production Infrastructure Options Evaluation. C.E. Thomas and I.F. Kuhn, Jr. NREL/TP-463-7903. UC Category 1360. DE95009276. September 1995.

[2] Issues in Midterm Analysis and Forecasting 1996. Energy Infromation Administration. DOE/EIA - 0607(96). September 1996.

[3] CAES Status and the AEC 110 MW Plant. Eric Swensen. Energy Storage and Power Consultants. New Jersey. Proceedings of the Energy Storage Association Spring Meeting 1997. Washington, D.C.

There are no comparable HES systems in existence in the electric utility sector. However, there are numerous studies that have assessed the current and projected cost of hydrogen energy storage system. This report uses such data to compare the cost of HES systems with that of other storage systems in order to draw some conclusions as to the applications and the cost-effectiveness of hydrogen as a electricity storage alternative.

1.1 APPROACH

Cost information on existing and planned Battery Energy Storage (BES), Superconducting Magnetic Energy Storage (SMES), and Flywheel Energy Storage (FES) demonstration projects were solicited from the vendors and the end-users. Initial contact with the utilities and the vendors was made by mail. Subsequent telephone discussions and site visits were conducted to gather more detailed information.

Since most companies consider cost information to be proprietary, each vendor was assured that they would be given an opportunity to review the data to be included in this report prior to its publication. This encouraged the companies to discuss cost issues as openly and candidly as possible. Each vendor was sent a detailed summary of the discussion and was permitted to delete any information they considered to be proprietary.

The quality and quantity of cost information that was obtained for this report varied greatly depending on the state of the technology (commercial vs. developmental), the status of the specific demonstration projects, as well as the particular vendors. For example, the cost-breakdown of many operational BES projects could be obtained with a great degree of accuracy, while vendors were justifiably reluctant to discuss new or planned projects. While the report presents all the information that was acquired, the emphasis for comparative purposes is on the percentage of cost associated with three key components of the energy storage systems, namely:

- Storage Subsystems
- Power Conversion Subsystems (PCS)
- Balance of Plant (BOP)

Vendor estimates on the potential for further cost reductions are presented as a percentage reduction in each of these three categories.

Hydrogen energy storage (HES) systems have not been considered in much detail for electric utility application. However, costs of individual components of HES systems have been well document by Energetics, Inc. and Directed Technologies, Inc. This report utilizes that data for comparing hydrogen with the other storage technologies.

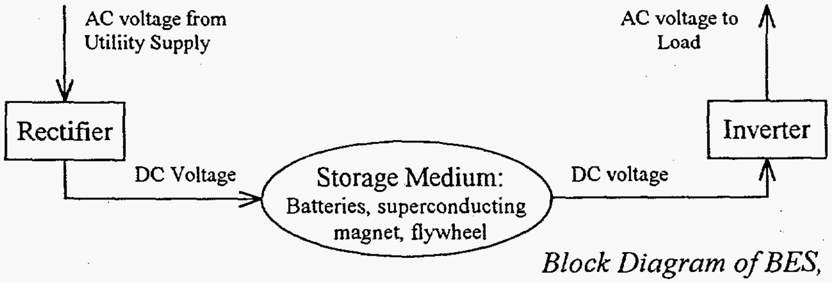
2.0 OVERVIEW OF ENERGY STORAGE SYSTEMS AND COMPONENTS

Typically energy storage systems are composed of three key components, namely the storage subsystem, power conversion subsystem, and balance of plant. The four ES systems investigated in this report are Battery Energy Storage (BES), Superconducting Magnetic Energy Storage (SMES), Flywheel Energy Storage (FES), and Hydrogen Energy Storage (HES).

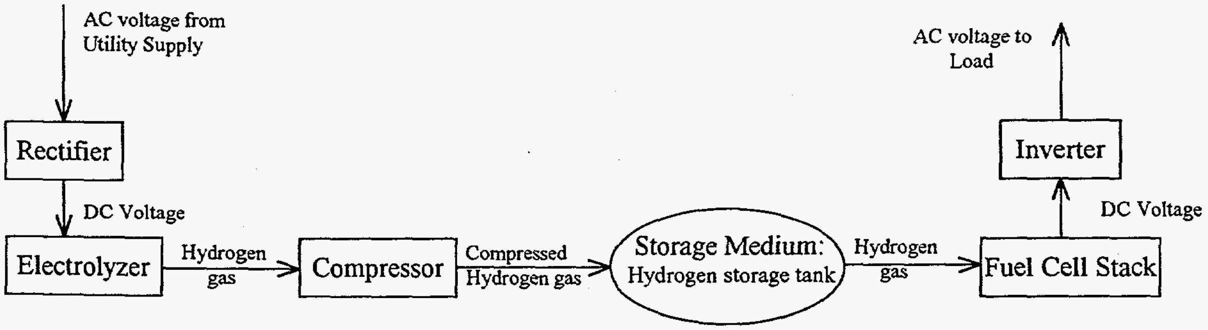
Among the four, BES is the closest to being available on a commercial scale, followed by SMES, which has been installed at several industrial sites for power quality applications. Low-loss, high speed FES systems mounted on magnetic bearings, primarily developed for automotive applications, are in the preliminary design and testing stages for utility scale applications. Components of the HES system are in various stages of development. Some are available commercially. Although a utility-scale HES system can be assembled and demonstrated with available components, it has not yet been undertaken except for small demostration projects.

Figure 2.0 illustrates in the form of a simple block diagram the different pieces of equipment required for a HES system compared to the three other storage systems considered in this report.

Fig 2.0: Block Diagram of a HES system compared to BES, SMES and FES systems



Block Diagram of BES, SMES and FES Systems



Block Diagram of HES Systems

In order to store electricity in a HES system, an electrolyzer is required to produce hydrogen. The hydrogen produced is stored in pressurized steel, aluminum or carbon fiber containers. A fuel cell is used to convert the stored hydrogen into electricity. The power conversion subsystem (PCS) converts the alternating electricity supply waveform to direct current to feed the electrolyzer. The PCS then reconverts the direct current generated by the fuel cell to an alternating current and feeds it to the load.

The storage subsystem for BES consists of battery modules that are connected in series to form strings; and the strings are in turn connected in parallel to provide the required rating for the battery subsystem. Though a variety of battery technologies are available, the most common commercially available technologies for utility applications are flooded lead-acid battery and valve regulated lead-acid (VRLA) battery. Hardware associated with the installation of these batteries includes interconnects, fuses, racking, protective guards and fire equipment. In addition flooded lead-acid batteries require spill troughs, watering systems and venting. The storage subsystem for a BES is explained in Section 2.1 and the main components of the BES system are illustrated in Fig 2.1.

A SMES storage subsystem consists of a superconducting magnet that stores energy in a magnetic field. This magnetic field is created by the flow of direct current in a coil of superconducting material. The storage subsystem consists of the magnet, leads, enclosure, thermal shield, cryogenics, pumps, vent, and other components. Section 2.2 describes the storage subsystem and its operation, and Fig 2.2 shows the main components of SMES. The storage subsystem of a FES consists of a flywheel which stores energy in the form of kinetic energy. The flywheel spins at very high velocities (tens of thousands of revolutions per minute) and consists of the flywheel, radial and thrust magnetic bearings, center post, containment, and other components. Section 2.3 explains the operation of a FES system while section 2.4 explains the operation of a HES system.

The power conversion subsystem for all four systems consist of a combination of rectifier/inverter, transformer, DC and AC switchgear, disconnects, breakers, switches, and programmable high speed controllers. A high speed motor/generator set is part of the power conversion system in the FES system. High speed solid-state transfer switches are used in power quality applications where high switching speeds are a requirement for the energy storage system. Section 2.5 explains the operation of the PCS.

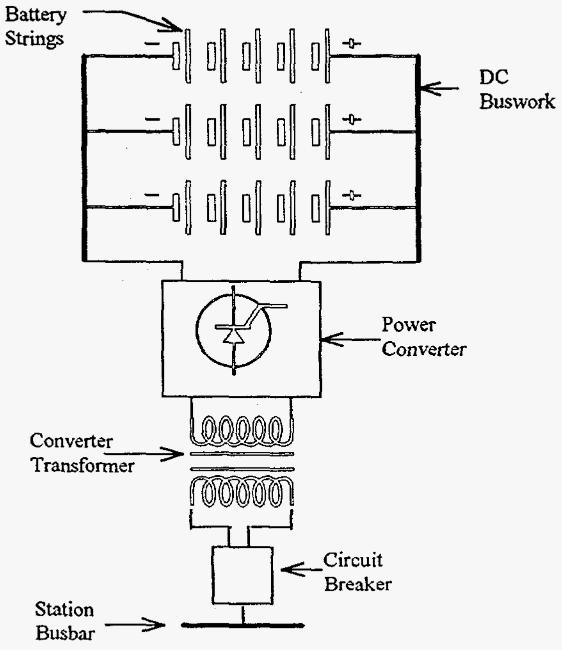
The control system for ES systems has three main functions. The management and control of storage subsystem monitors the charge level, charge/discharge requirements, and related operations. The controls associated with the PCS subsystem monitors utility power supply and switches the load between the ES system and utility supply according to a predetermined algorithm. The facility control system monitors the temperature, ventilation and lighting in the facility which houses the hardware. Each of these three control systems will be discussed when describing the relevant subsystems they control.

The balance of plant costs of BES, SMES and FES encompasses the facility to house the equipment, heating, ventilation and air conditioning (HVAC) the interface between the ES system and the customer/utility, the provision of services such as data gathering/trending, project management, transportation, permits, training, spares, and finance charges. In addition to the balance of plant items listed, the HES system also requires additional equipment such as electrolyzer, compressor, fuel cell and associated equipment which forms the core of the HES systems. The cost of the balance of plant is a variable component both between and within the four technologies and, to a large extent, is determined by the needs of specific sites and applications.

2.1 ENERGY STORAGE SUBSYSTEM FOR BES

A Battery Energy Storage System consists of several components as shown in Figure 2.1 below. The main hardware of the BES consists of batteries, the power conversion system and the control system.

Figure 2.1: Main Components of BES System



A battery module's basic building block is the electrochemical cell. At times a number of electrochemical cells are packaged together to form a battery module. The battery modules are connected in a matrix of parallel-series combination to form a string. A string may be formed to deliver the required voltage which may range from a few hundred volts up to approximately 2,000 volts. The string voltage is selected to minimize the power converter and buswork costs.

The life of a battery and its energy delivery capability is highly dependent on the manner in which it is operated. In general, many deep discharges reduce battery life. High rates of discharge reduce the energy delivery potential of the battery. For example, a 1MW/1MWh BES discharged at 1 MW will be able to supply the entire 1 MWh of stored energy over a 1 hour period. However, if discharged at a 2 MW rate, the battery will operate for less than half an hour, delivering less than 1 MWh of energy in the process.

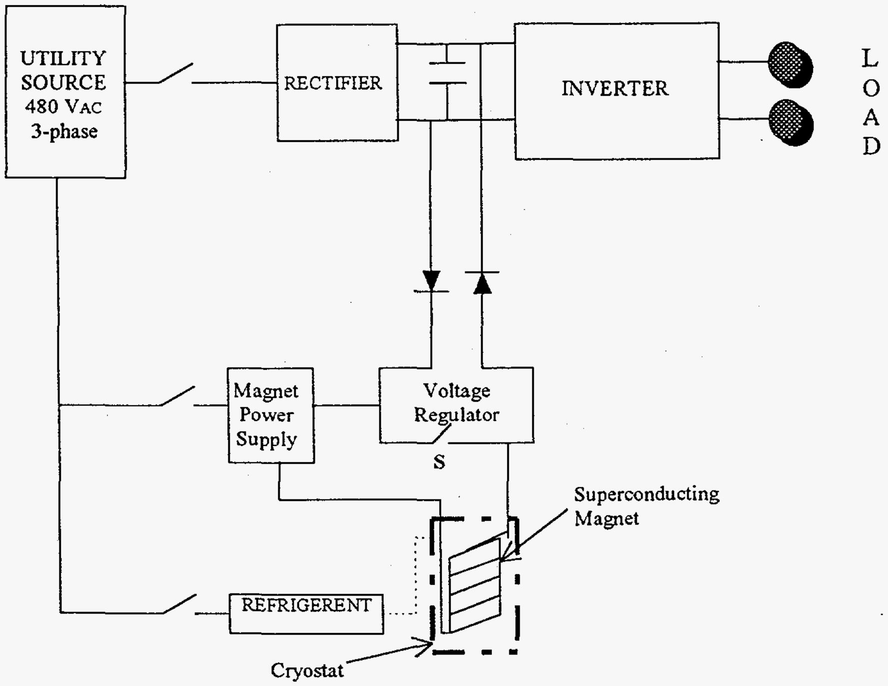
The life of a battery is affected by the manner in which it is operated. The cycle life (the number of charges and discharges it can perform) of a battery is highly dependent on the depth of discharge, with deep discharges (>70-80 percent) significantly reducing its cycle life. Batteries also have shelf life limitations.

Flooded and valve regulated lead-acid batteries are two commercially available battery technologies for utility applications. Advanced batteries such as sodium/sulfur (Na/S) and zinc/bromine (Zn/Br) are being developed and may soon be commercially available.

2.2 ENERGY STORAGE SUBSYSTEM FOR SMES

A Superconducting Magnetic Energy Storage (SMES) System consists of several components as shown in Fig 2.2. Though large SMES systems (10-100 MW, with storage times of minutes) are under development, smaller units (1-10 MW, with storage times in seconds) are becoming commercially available to serve the power quality market. Larger SMES systems are anticipated to store thousands of MegaJoules (MJ) of energy while the smaller micro-SMES systems are expected to have 1-10 MJ (0.28-2.8 kWh) of energy storage capability.

Figure 2.2: Main Components of a SMES system



The main hardware of a SMES consists of the magnetic storage unit, the cryostat, and the power conversion system. The superconducting system stores energy in the magnetic field created by the flow of direct current in a coil of superconducting material. To maintain the coil in its superconducting state, it is immersed in liquid helium contained in a vacuum-insulated cryostat. Typically, the conductor is made of niobium-titanium, and the coolant can be liquid helium at 4.2 K, or super fluid helium at 1.8 K. In the standby mode, the current continually circulates through the normally closed switch '*S*', as shown in Fig 2.2. The power supply continuously provides a small trickle charge to replace energy lost in the non-superconducting part of the circuit in the standby mode.

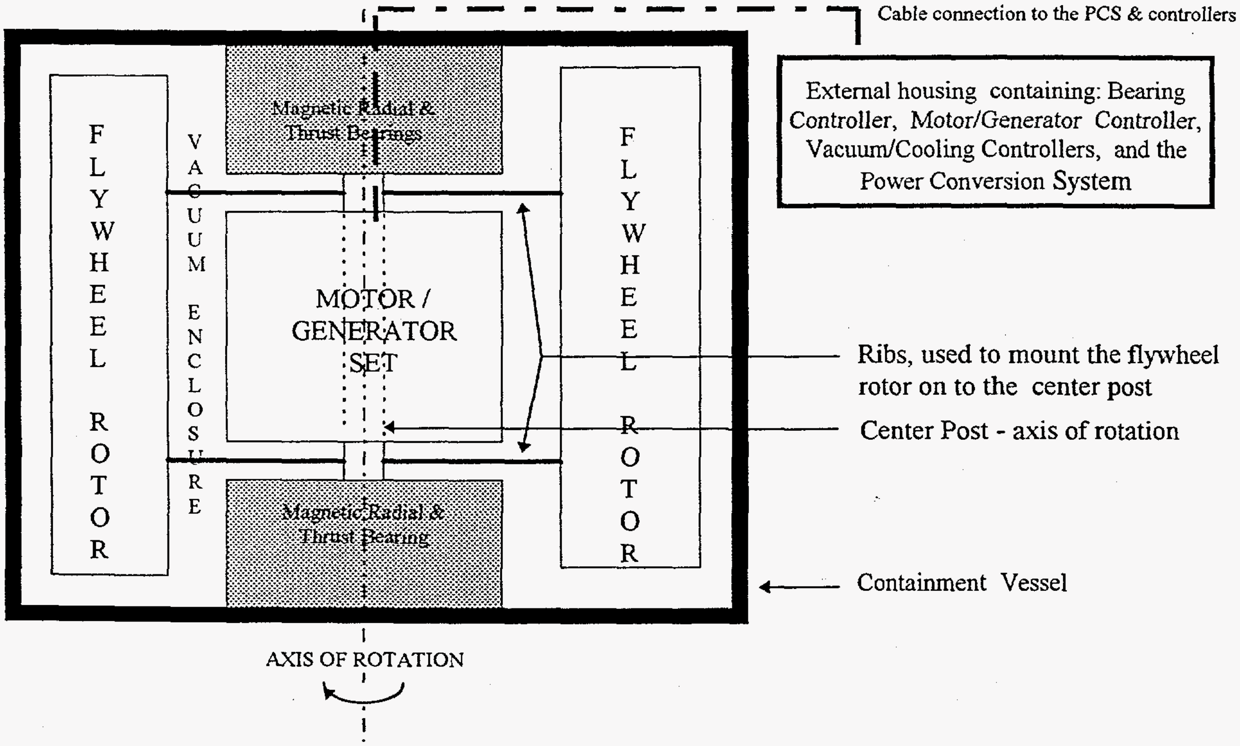
2.3 ENERGY STORAGE SUBSYSTEM FOR FES

Flywheel Energy Storage (FES) systems are under development primarily for automobile and space applications. Though the concept of flywheels is not new, low loss flywheels which rotate on magnetic bearings in a levitated state at very high speeds are a relatively new development.

The FES for electric utility applications does not have many of the dynamic isolation problems which have to be overcome for automotive applications. Small kW/kWh scale systems for power quality applications are now available in the commercial market.

The stored energy in flywheels is proportional to the flywheel's moment of inertia multiplied by the square of its angular speed. Therefore, high velocities are required to store large amounts of energy. Flywheels with speeds of tens of thousands of revolutions per minute (RPM), up to 100,000 RPM, have been tested. The flywheel configuration is driven by the need to have the maximum moment of inertia for a given weight. Economics dictate the use of light weight composite materials to withstand the stresses created during the high speed operation of the flywheel. The use of magnetic bearings and a vacuum chamber helps reduce losses.

Figure 2.3: Cross-Sectional View of the Flywheel Containment Vessel



A motor/generator set is mounted on the same center-post as that of the flywheel, and rotates at the same speed as that of the flywheel. The configuration shown in Fig 2.3, has the motor/generator set mounted within the flywheel rotor. The vertical center post rests on bearings. The entire assembly is enclosed within a vacuum containment vessel. The configuration allows for compactness and reduction of rotational losses. The electrical leads from the motor/generator set is brought out of the vacuum containment and connected to PCS. The controllers of the motor/generators, bearings, vacuum/cooling system, the PCS and its controllers are all housed outside the containment.

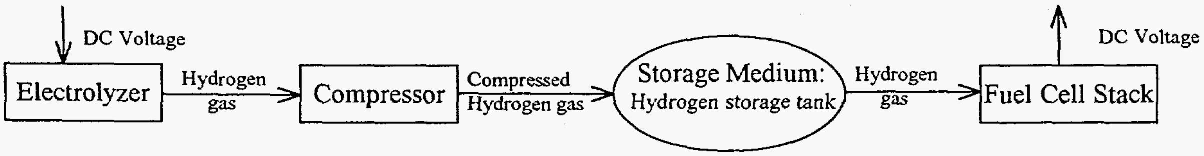
A FES can be optimized either for power or energy. Large power ratings require large motor/generators, which themselves have the ability to store large amounts of kinetic energy due to their large mass and high rotational speeds. Optimization for energy will require relatively larger flywheels to store energy, since the smaller-sized motor/generator (smaller power rating) will not be able to store large amounts of energy. The motor/generator housed within the flywheel is typically a permanent magnet, brushless, dc drive commutated electronically. The dc voltage output of the motor/generator set has to be conditioned by a typical power conversion system to interface with the external supply and load.

Stress/strain cycles are created in the flywheel as the velocities change. In order to maintain constant voltage as the speed varies and to reduce these stress/strain cycles the system is not allowed to slow down completely. It is similar in concept to electrochemical batteries where a high depth of discharge reduces the life of the battery. The thrust bearings of FES systems will also have to be periodically replaced.

2.4 ENERGY STORAGE SUBSYSTEM FOR HES

The energy storage subsystem include the electrolyzer, compressor, storage vessels and fuel cell stacks.

Fig 2.4: Block Diagram of Energy Storage Subsystem of HES



The most economical method of hydrogen production today is by the process of steam reforming natural gas. However, when considering HES systems to store electricity, electrolyzers provide the only technology option. Alkaline water electrolyzers are commercially available. Solid polymer electrolyzers, developed originally for space applications, are now being developed and are expected to exhibit higher conversion efficiencies.

Among the fuel cell technologies, phosphoric acid fuel cell (PAFC) are in early stages of commercial scale manufacture. Other technologies, including Proton Exchange Membrane fuel cell (PEMFC), Solid Oxide fuel cell (SOFC), and Molten Carbonate fuel cell (MCFC) are also under development. Among the four fuel cell technologies, PEMFC possibly holds the greatest potential due to its projected high efficiencies, low temperature operation, and potential cost effectiveness.

In principle the electrolyzer and the fuel cell can be combined into one unit - a reversible fuel cell/electrolyzer. During off-peak hours this unit serves as an electrolyzer producing hydrogen, while during peak hours it functions as a fuel cell to convert the stored hydrogen into electricity. The advantage of a reversible system obviously is lower capital cost. However, this advantage must be compared against the draw back of lower efficiency, increased corrosion and other significant technical hurdles. At present R&D is in progress on reversible H_2-O_2 and H_2-Br_2 systems, however, not enough data is available to determine the practicality of such a system

The hydrogen produced in the electrolyzer is pressurized by a compressor in order for it to be stored in smaller containers. High pressure hydrogen storage vessels made from steel, aluminum and carbon fiber are available at up to 400 atmospheric pressure (6,000 psi).

2.5 POWER CONVERSION SUBSYSTEM

The power conversion subsystem used by all four storage technologies operate under similar principles. The power converter consists of a combination of rectifier/inverter and a transformer where needed. When the storage subsystem is being charged, the converter behaves like a rectifier, changing the ac voltage into dc. When discharged, or when it is supplying power to the system, the converter operates as an inverter.

In the rectifier mode the converter controls the voltage and the charging current. The voltage and the resulting current are adjusted for the desired charge rate. The conversion of ac voltage to dc is achieved by firing the thyristors so that the voltage from the transformer windings cause the desired current to flow to the storage subsystem. In the inverter mode, the converter essentially chops the dc current into segments and builds a voltage wave that is an approximation of the normal ac system sine wave.

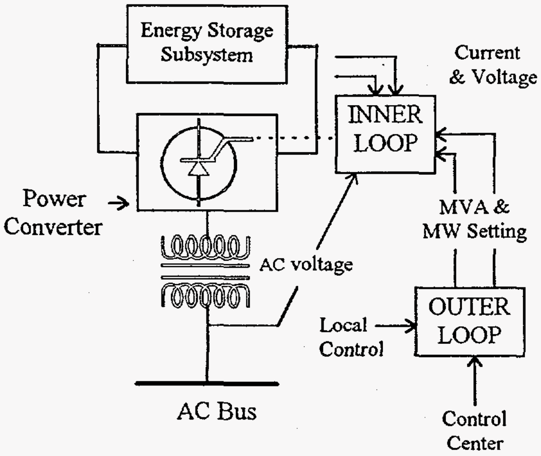
The converter causes power to flow into the ac bus by shifting its waveform (the ac waveform created from the dc bus voltage) ahead of the waveform of the bus voltage. Reactive power is delivered by making the magnitude of the waveform larger than that of the ac bus voltage.

Converters are normally given ratings in MVA, but this rating only applies at rated voltage. Converters are, in reality, current-limited devices. A converter can be used to provide active or reactive current or a combination within its current handling capability. Because real and imaginary current are in quadrature, the square root of the sum of the squares of the reactive and active currents must remain within the converter current capability. A 10 MVA converter can thus supply 7MW/7MVAR, 8MW/6MVAR, 6MW/8MVAR, etc. at rated voltage.

The power conversion control is generally divided into two loops. The 'inner loop' provides high speed regulation of the energy storage subsystem. For instance, if the battery is being controlled to a certain power level, the controller will adjust the thyristor firing pulse so that power is maintained even when the bus voltage varies. The controller will also go into a current control mode when a drop in voltage requires converter current to rise above the converter rating to maintain power. Figure 2.5 illustrates a power conversion and control subsystem.

The inner loop may also include voltage control circuitry. This circuitry adjusts firing pulses to the thyristors so that the converter will produce or absorb reactive current as needed to regulate bus voltage. Again, the controller will go into a current control mode if the thyristor current would have to exceed thyristor rating in order to hold the desired bus voltage. The converter effectively synthesizes a waveform that is either larger or smaller in magnitude than the bus voltage, and either leads or lags the bus voltage. The voltage and power level control circuitry operate simultaneously to control the magnitude and phase of the waveform, respectively.

Fig 2.5: **POWER CONVERSION & CONTROL SUBSYSTEM**



The 'outer loop' control is slower, and typically is a desired power level signal received from the system control center. It could be provided by the automatic generation control system, and could be similar to the raise and lower signals sent to generating plants. It may also be just a time clock that schedules charge and discharge times so as to coincide with system peak load and low load periods, respectively. The outer loop may also include a stabilizer to modulate power when oscillations in line power or frequency occur.

Currently electrolyzes and fuel cells have their own power conversion systems, with a rectifier in the electrolyzer and the fuel cell having an inverter. In an integrated HES system where the electrolyzes and fuel cells are in close proximity, the two PCS systems can easily be integrated into one optimized cost-effective system. That will also be true if the DOE Hydrogen Program is successful in developing a reversible fuel cell/electrolyzes system. Since, no such integrated PCS has been produced for HES applications to-date it is very difficult to estimate its cost. For the purpose of this report, the assumption is made that the projected cost of such a system will be very similar to those for the three other ES systems considered in this report.

The control system of HES is different from that of others energy storage systems in that it must control the flow of hydrogen gas to the fuel cell when supplying the load, in addition to the control of the solid state devices in the power conversion systems. The control system must also include the necessary controls to cycle the electrolyzer and compressor during the utility off-peak and peak demand hours. Safety sensors will also have to be monitored continuously.

2.6 BALANCE OF PLANT

Balance of plant, as discussed earlier, encompasses the facility to house the equipment, HVAC, and the interface between the ES system and the customer/utility. In addition to buildings and interface equipment, the provision of services, such as data gathering/trending, project management, transportation, permits, training, spares and finance charges add substantial cost to storage systems.

BES, SMES, and FES systems available at present are not off-the-shelf products (with the exception of some power quality systems), and are custom-sized depending on the needs of each customer. The incidental cost particular to custom-built systems has added considerable cost to each of the systems now in operation. The balance of plant cost for the 20 MW/14 MWh BES in Puerto Rico, consisting of building of the facility, load interface, O&M, services, finance charges and taxation account for 46 percent of the total project cost of $21.4 million. Building of the facility accounted for 22 percent while load interface, O&M, services, finance charges and taxation accounted for 3%, 3%, 9%, and 9% of the total project cost, respectively.

The balance of plant costs of storage systems for power quality applications, on the other hand, are much lower in percentage terms. This could be attributed to uniform off-the-shelf product lines to serve a well defined application. The lower energy storage requirements of power quality systems make them compact and enables the entire system to be housed within a container, making them easier to transport.

The balance of plant for the battery-based PQ2000 product line accounts for 27 percent of the system cost, with load interface, delivery/installation/support, taxes, and services accounting for 5%, 5%, 7%, and 10% of the system cost, respectively. Preliminary estimates for the cost of balance of plant for the SSD® product line (a micro-SMES system developed by Superconductivity, Inc.) is estimated to be approximately 40 percent.

Since commercial FES systems are not available, costs associated with balance of plant were not available. An important feature of the FES system is that a separate building will not be necessary, since the flywheel along with its containment vessel, in most instances, will be placed underground. Since the containment is housed below the surface, the cost associated with erecting a building is minimized. However, the power conversion system, the bearing controller, the motor/generator controller, and the vacuum/cooling systems, all have to be housed separately above ground.

Since HES systems for electric utility application has not been demonstrated, very little information is available with regards to its BOP costs. A preliminary capital cost estimate (Suman Sigh study)[4] for a hydrogen dispensing station, utilizing a steam methane reforming process, estimates the non-equipment cost associated with the dispensing station to be about 30 percent of that of the total project cost.

The equipment cost of a HES system will include the cost of the electrolyzer, compressor, hydrogen storage tanks, and the fuel cell. Among these equipment, the cost associated with the hydrogen storage tanks (the storage subsystem) is the least. In addition, the rectifier, inverter, and control system costs will constitute the PCS subsystem cost. If the hydrogen storage tanks alone are considered the storage subsystem (since it is the only cost component which will increase with storage duration), and the cost of the electrolyzer, compressor and fuel cell are considered as part of the traditional BOP cost, the BOP cost of HES systems will account for more than 80% of the total project cost.

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[4] Hydrogen fuel dispensing stations for transportation vehicles. Sumanm Sigh. Oak Ridge National Laboratory. ORNL/TM-12982. October 1995.

3.0 ENERGY STORAGE SYSTEMS FOR UTILITY APPLICATIONS

The Opportunities Analysis Study[5] identified the various application of ES systems in the electric utilities. Table 3.1 lists those applications and the energy storage system characteristic required to meet the application needs.

Table 3.1: Summary of Applications Requirements

Application	Approximate Power (MW)	Approximate Storage (hours)	Voltage (kV_{ac})	Cycles/ year
GENERATION				
Spinning Reserve	10 - 100	0.5	12- 138	20 - 50
Capacity Deferral	10 - 100	2 - 4	12 - 138	5 - 100
Area/Frequency Regulation	10	<1	12 - 138	250
Integration with Renewables	1	1 - 4	0.48 - 12	250
Load Leveling	100	> 4	69 - 765	250
TRANSMISSION & DISTRIBUTION				
Transmission Line Stability	100	<0.01	69 - 765	100
Voltage Regulation	1 MVAR	<0.25	12 - 34.5	250
Transmission Facility Deferral	10	2 - 4	12 - 138	5 - 20
Distribution Facility Deferral	1	1 - 3	4 - 34.5	30
CUSTOMER SERVICE				
Demand Peak Reduction	1	1 - 2	0.48 - 12	50 - 500
Transit System Peak Reduction	1	1 - 2	0.48 - 2.4	250 - 500
Reliability & Power Quality (<1 MW)	0.1	< 0.25	0.48	<10
Reliability & Power Quality (>1 MW)	1	1 - 2	0.48 - 12	<10

A brief description of each of the application are included in Appendix A. Table 3.1 categorizes the applications in terms of the three traditional functions that an electric utility provides. These applications can also be sub-divided into three categories based on the energy storage duration and are listed in Table 3.2. The required storage durations of some applications may overlap between two categories. The table also indicates storage technologies best suited to meet the application requirements. Suitability is based on technological and operating characteristics, and the potential of BES, SMES and FES to compete in terms of capital cost with conventional generation technologies in the short/medium term; and HES based on substantial cost reduction in the long term.

The first category requires storage time of less than a second to a maximum of one-half hour. Reliability and power quality applications at the customer end, with relatively small power rating (< 1MW) fall into this category. Traditionally uninterruptible power systems (UPS) were used for this purpose, but with increased automation of manufacturing processes larger storage systems must be installed to maintain the high degree of reliability and power quality. High power, low

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[5] Battery Energy Storage for Utility Applications: Phase I - Opportunities Analysis. Paul Butler. Sandia National Laboratories. SAND94-2605/UC-212. October 1994.

Table 3.2: Suitability of Storage Systems for Utility Applications

Category of Application	BES	SMES	FES	HES	Remarks
Storage Duration: seconds to 0.5 hours					
Reliability & Power Quality	* * *	* * *	* * *	X	Domain of UPS, where batteries are used. SMES becomes competitive at larger power ratings and short duration (seconds) protection. FES systems becoming available for this market. Low power rating and short duration storage makes HES unsuitable.
Transmission Line Stability	* *	* * *	* *	X	BES and SMES units in operation/under construction for this application. HES unsuitable due to intermittent use and short storage duration.
Voltage Regulation	* * *	* * *	* * *	X	BES and SMES units in operation/under construction for this application. Intermittent operation and small storage requirement makes HES unsuitable.
Storage Duration: 0.5 hours to 2 hours					
Reliability & Power Quality	* * *	X	* *	X	Larger duration protection at customer end makes SMES expensive. Protection durations >1 hour is the domain of batteries
Spinning Reserve	* * *	* * *	* * *	X	Suited for BES, SMES, FES technologies, made possible by fast-acting power electronics. BES and SMES units in operation/under construction for this high power application. High capital cost of HES makes it unsuitable for intermittent short duration usage.
Area/Frequency Regulation	* * *	* * *	* * *	X	Quick response time makes storage attractive. BES serving this application exist.
Transmission Facility Deferral	*	X	X	*	Requires large energy storage at high power levels, which at present precludes SMES and FES. HES may serve this application with substantial cost reduction
Distribution Facility Deferral	* *	X	*	*	High energy requirements makes SMES uncompetitive. Economics of BES and FES and HES may be justified depending on the site.
Demand Peak Reduction	*	X	*	*	High energy requirement precludes SMES. Present tariff structure makes the application unjustifiable. However, combining it with power quality BES and FES applications makes it attractive. HES feasible when inexpensive electricity is available seasonally.
Transit System Peak Reduction	* *	* *	* *	X	BES built for this application. FES under investigation to be mounted on locomotives. Economics precludes HES for short duration storage.
Storage Duration: >2 hours, regular cycling					
Load Leveling	X	X	X	*	Uncompetitive due to present capital cost structure. Large amounts of energy storage for long durations makes SMES uncompetitive at present. HES is suited, however, cost reduction and efficiency improvement necessary.
Renewable Applications	* *	X	* *	* *	Economics of firming up intermittent renewable generation to supply reliable energy is still under debate. Energy consumption by the cryogenics and refrigeration in SMES makes it unsuitable for long term (diurnal) storage. Conversion inefficiencies makes HES less attractive for short term storage. HES is attractive for long term storage.
Generation Capacity Deferral	X	X	X	*	Uncompetitive due to present capital cost structure. Economics of SMES at present is for relatively low energy storage levels. FES can be optimized either for power or energy - application requires both. HES may be feasible with substantial cost reduction.

* -- Indicates level of attractiveness/suitability, X -- indicates unsuitability

duration storage systems can also successfully meet application requirements for transmission line stability and voltage regulation.

The second category of application require energy storage from one-half hour to two hour duration. Examples of applications that fall in this category include, spinning reserve, frequency regulation and other T&D related applications. Power quality applications requiring longer duration protection also falls in to this category. In addition to relative short duration storage requirement, these applications also require very intermittent operation. The system is not cycled on a regular basis but must be available to supply the stored energy on demand, relatively quickly.

The third category of applications, in contrast to the first two, requires longer duration storage at larger power ratings and regular cycling of the system. Examples of applications that fall in the category include load leveling where off-peak, inexpensive electricity is stored for supply during peak periods. Another potential application is the storage of intermittent renewable generation for longer duration, i.e. days and/or weeks. Such circumstances can easily arise particularly for off-grid application when the solar or wind resources may not be available for days at a time.

The energy available in a SMES system is independent of the discharge rate. This characteristic along with its quick response time makes SMES suitable for applications which require high power in short energy bursts. The high cycle life of a SMES systems makes them more suitable for applications which require constant cycling.

At present, the capital costs of a SMES system is high. Even then, for power quality applications such as to guard against voltage sags and momentary outages, SMES systems are emerging to be cost-effective solutions. This is particularly true in the case of advanced automated manufacturing process which are susceptible to power fluctuation which typically last a few power cycle. With increased manufacturing volume and better design SMES system costs are expected to decline significantly. With substantial cost reduction SMES may also become cost-competitive with other storage technologies for other dynamic operating application as indicated in Table 3.2. In the past very large SMES systems were considered for load leveling applications. There is considerable controversy regarding the merits of SMES for such applications.

This study suggests that the projected capital cost and parasitic loads[6] makes SMES less attractive for competitive diurnal storage applications such as generation, transmission, and distribution capacity deferral, load leveling, customer peak reduction and renewable applications. In continuous mode operation, the system is constantly cycled and the parasitic losses are proportionally less. Typically these applications also require instantaneous discharge on demand, a characteristic SMES systems are well equipped to handle. In diurnal storage applications, parasitic losses are proportionally large, thus reducing overall system efficiency.

Conventional flywheels operating at low speeds (<1,200 RPM[7]) are used at present as load stabilizers to smooth out large power variations exhibited by drag-lines in coal mines. Insufficient

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[6] The Market Potential for SMES in Electric Utility Applications. An Arthur D. Little Inc. report prepared for Oak Ridge National Laboratory. ORNL/Sub/85-SL889/1. Exhibits 4.1-4.6 & 11.2

[7] FES system installed at the Usibelli Coal Mine, Alaska.

data are available to determine the suitability of high-speed, low-loss FES for diurnal storage cycling, however, power quality systems are becoming available in the market. Some interest has been shown for the use of FES systems in renewable generation applications, and for the installation of MW/kWh scale FES systems in distribution substations.

Battery Energy Storage (BES) has been receiving considerate attention from the electric utility industry. During the late 1970's and early 1980's, BES was considered a viable option for large scale load leveling applications. However, the present cost structure of BES, like that for SMES and FES, makes them less competitive for applications that require high power (MW scale) for long durations (>1 hour). It is becoming increasingly clear that these storage technologies cannot be viewed as energy supply technology, serving applications such as load leveling and generation capacity deferral, as the economics are not advantages to operate in such a mode. This trend could be observed in the recent systems built. They have large power ratings, but are designed to operate for durations < 1 hour. Examples include BES systems in PREPA (1994), Vernon (1995), Metlakatla (1996), Golden Valley (planned) and SMES in Anchorage (construction to begin shortly).

In general, fast-acting power conversion and control systems and the rapid response time of BES, SMES and FES storage technologies, makes these storage systems well suited for dynamic system operations. Dynamic operation applications such as transmission line stability and voltage regulation typically require power cycles in durations of minutes. Spinning reserve and area/frequency regulation applications require a longer (but typically less than 1 hour) durations of storage.

In contrast, HES's niche will be for applications which require long duration of storage, provided substantial cost reductions are achieved. Due to the low cost of hydrogen storage containers, the marginal cost of additional storage is minimal. Hence it is best suited for long duration storage applications such as generation, transmission, and distribution facility deferrals. However, due to the anticipated lower conversion efficiencies HES may not be best suited for integration with renewable systems unless storage durations of the order of days is required.

BES, SMES and FES technologies also seem to be capable of meeting the technological requirements of customer-end power quality equipment. However, HES system due to its longer start up time will not be able to serve this application.

4.0 COMPARISON OF ENERGY STORAGE SYSTEMS

Applications of electric energy storage systems can be classified into two broad categories depending on the storage duration and the rate at which these devices have to supply the stored energy.

One group of applications require instantaneous, high rate supply of the stored energy but for relatively short duration (<15 minutes). In addition, events that require such systems occur randomly and ES systems are therefore not cycled periodically. This class of application are gaining increased importance as high quality uninterrupted power is becoming an absolute necessity in advanced automated manufacturing systems. Recent estimates by EPRI and others suggest that productivity losses associated with power quality problems range between $50 billion to $400 billion. BES, SMES and FES are either commercially available or are being developed to meet such application requirements at the customer-end.

Renewable resource based HES systems, because of their significant capital costs, are not suited for the infrequent and intermitted use, as given in Table 3.2. Since this report attempts to establish baseline costs for ES systems with which HES systems must compete, no further consideration will be given to ES systems that are used predominantly for power quality applications.

The second group of applications requires large amounts of storage for a significantly longer duration (>1hr). The system in this application will be required to deliver energy for extended durations. Load leveling, peak shaving, off-grid renewable/storage applications are some of the applications that fall in this category. An important characteristic of these application is that the ES systems are used on a daily basis. Both DOE and EPRI have supported the development of energy storage systems for such applications for over two decades. Theoretically, both SMES and FES systems can meet these application requirements. Early cost estimates indicated that large SMES systems would require very high capital investments and all development activities for such SMES systems were terminated. Currently there is no SMES or FES systems that are being developed for this class of applications and these systems will not be considered any further in this cost analysis. However, estimates of present and projected costs of SMES and FES systems are tabulated in Table 5.5, along with BES systems, without further analysis.

BES and HES systems are the likely candidates for long duration applications. Several commercial scale BES plants are in operation while no demonstrations of HES systems are in progress now. Some HES systems validation efforts are expected to commence relatively soon. In this report, the actual BES system costs for existing systems as well as projected costs of future systems are compared with the projected cost of future HES systems.

In order to evaluate the relative merits and market segments of BES and HES systems, the variation of equipment cost with duration of storage could be assessed. The present and projected capital cost data of the various components of a 1-10 MW system is tabulated in Table 4.1.

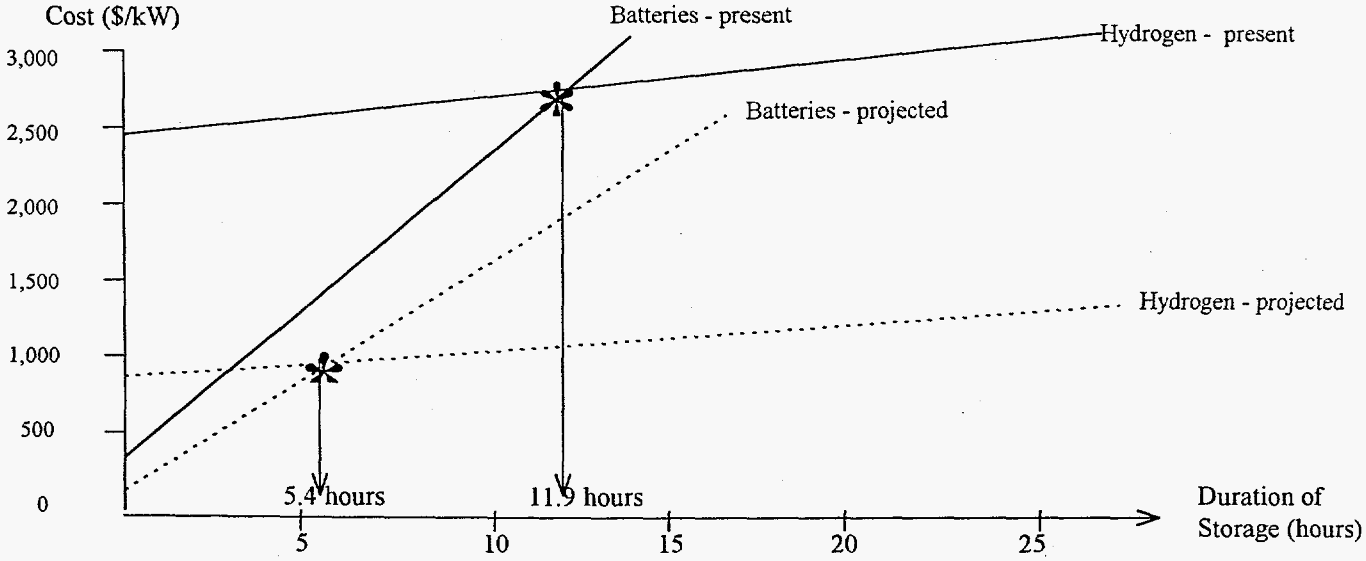
Table 4.1: Present and Projected Equipment Cost of BES and HES Systems

	Present	Projected
<u>**BES SYSTEM**</u>		
Electrochemical Battery	$200/kWh	$150/kWh
Power Conversion System	$300/kW	$150/kW
<u>**HES SYSTEM**</u>		
Pressurized hydrogen Container	$20/kWh	$15/kWh
Electrolyzer	$700/kW	$300/kW
Compressor	$150/kW	$125/kW
Fuel Cell Stack	$1,000/kW	$300/kW
Power Conversion System	$600/kW	$150/kW

The present and projected BES costs were derived from interviews with equipment manufactures[8]. The HES system costs were obtained from estimates derived by Suman Singh[9], Joan Ogden[10], and C.E. Thomas[11].

Figure 4.1 plots the capital cost of a BES and HES as a function of the duration of storage required in the system. Cost data from Table 4.1 was used for this purpose. The key point to note in Fig 4.1 is that for both "present" and "projected" cost cases BES systems are cost-effective for shorter duration while HES systems would be preferred for longer storage duration. It is important to bear in mind that only equipment costs are included in this analysis, since estimating the installed cost of an HES system in the absence of any experience with an operating commercial scale system is difficult. Nonetheless, preliminary estimates suggest that the same overall trend will be observed when all cost issues are include.

Figure 4.1: Competitive Range of Hydrogen and Battery Storage based on Capital Cost of Equipment



Capital costs alone does not provide a good measure of the cost-effectiveness of a particular system and one must compare the life-cycle cost of the system as well. Such a comparison for a BES and HES system was conducted and is plotted in Figure 4.2. It plots the life-cycle cost as a function of the storage duration for BES and HES systems. The trend that was evident in Fig 4.1 is also quite evident in Fig 4.2, namely that BES systems are cost-effective for shorter storage

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[8] Cost Analysis of Energy Storage Systems for Electric Utility Applications. Abbas Akhil. Sandia National Laboratories. SAND97-0443.UC-1350. February 1997.

[9] Hydrogen Fuel Dispensing Station for Transportation Vehicles. Suman P. Singh and Andrea A. Richmond. Oak Ridge National Laboratory. 1995. ORNL/TM-12982

[10] Hydrogen Energy Systems Studies. Joan M. Ogden. Prepared for the Department of Energy, Contract No. XR-11265-2. 1995.

[11] Electrolytic Hydrogen Production Infrastructure Options Evaluation. C.E. Thomas and I.F. Kuhn, Jr. NREL/TP-463-7903. UC Category 1360. DE95009276. September 1995.

durations while HES systems are clearly superior for longer storage duration. Table 4.2 lists the assumptions that were made in conducting the life-cycle cost comparison.

Figure 4.2: Life Cycle Cost of BES and HES Systems

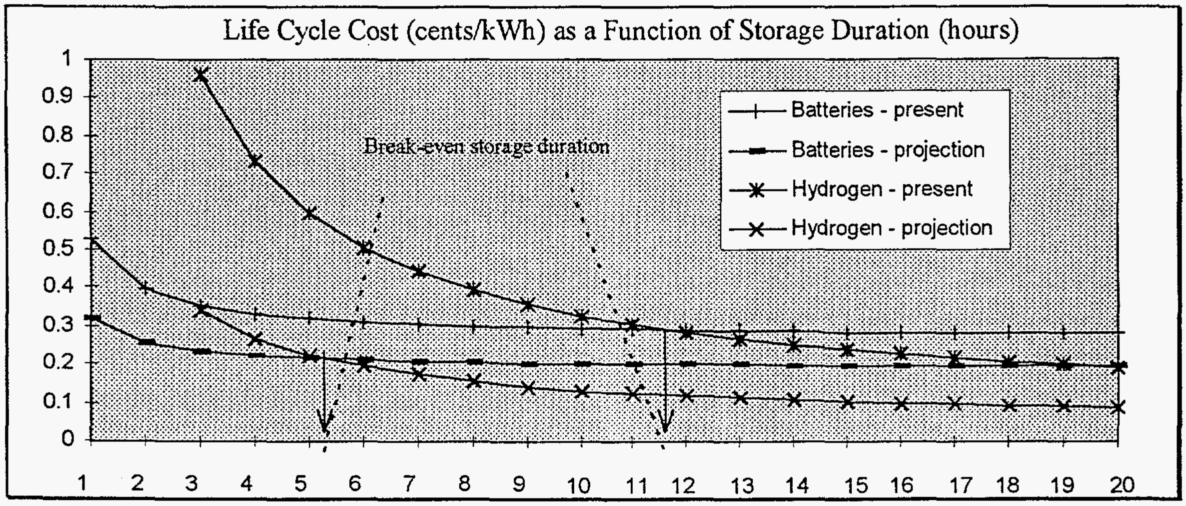


Table 4.2: Assumptions for Life Cycle Cost Comparison

	Present	Projected
BES SYSTEM		
Round-trip Efficiency	70%	75%
Off-peak electricity cost	1 ¢/kWh	1 ¢/kWh
Variable input electricity cost	1.43 ¢/kWh	1.33¢/kWh
Other Variable O&M cost	1 ¢/kWh	1¢/kWh
Life of Batteries	8 years	10 years
All other equipment	20 years	20 years
Balance of plant - % of Equipment cost	100%	100%
HES SYSTEM		
Round-trip Efficiency	35%	50%
Off-peak electricity cost	1 cent/kWh	1 cent/kWh
Variable input electricity cost	2.86¢/kWh	2¢/kWh
Other Variable O&M cost	1¢/kWh	1¢/kWh
Life of Fuel Cell and Electrolyzer	8 years	10 years
All other equipment	20 years	20 years
Balance of plant - % of Equipment cost	100%	100%

This analysis suggests that of the six energy storage systems, only the BES and HES systems could compete for similar applications. Several commercial scale BES systems are in operation. Actual capital cost data for these systems are discussed in the following sections. The objective in collecting that data was to establish a base line cost-data for the competing technology so that accurate cost target for HES systems could be established.

5.0 BATTERY ENERGY STORAGE PROJECTS

The following commercial scale BES projects are considered in the analyses:

- Puerto Rico Electric Power Authority (PREPA)
- Southern California Edison (CHINO)
- San Diego Gas & Electric (SDG&E)
- GNB Industries (VERNON)
- Metlakatla Power & Light (METLAKATLA)

In addition to these five projects, this report also contains cost information for a modular factory assembled BES device (PM 250) developed by AC Battery Corporation. Table 5.1 summarizes the cost of these six systems. The analysis of the cost data is divided into three segments reflecting the three key cost-components of the system, namely:

- Batteries & Accessories
- Power Conversion Systems
- Balance of Plant - System Integration & Facility Development

5.1 BATTERIES AND ACCESSORIES

The battery subsystem consists of individual battery modules connected in series to make up a battery string. Several battery strings, in turn may be connected in parallel to meet the power and energy requirement of the battery subsystem. The energy storage capability of the battery module, the basic building block, is fixed. Hence, the cost of a battery subsystem is primarily driven by its energy rating, and to a lesser, but significant, extent by its power ratings.

The capability of a battery to deliver its stored energy is dependent on the rate of discharge. High rates of discharge reduce the energy delivery potential of the battery. Due to these operating characteristics, there can be multiple power and energy ratings for a battery subsystem. The application specification of each location will determine the way the battery is discharged - however, the battery may at any given location serve more than one application. The power rating of a BES system to a large extent is restricted by the power rating of the power conversion subsystem.

Table 5.1: Cost of Projects & Products - Battery Energy Storage Systems

PROJECT/ PRODUCT	DESCRIPTION OF SYSTEM	COST OF STORAGE SUBSYSTEMS - constant 1995$			TOTAL COST - constant 1995$		
		STORAGE	PCS	BOP	$/kW	$/kWh	(000s of $)
PREPA[1]	20 MW/14 MWh BES	22% ($341/kWh)	27% ($294/kW)	51%	1,102	1,574	22,042
CHINO[2]	10 MW/40 MWh BES	44% ($201/kWh)	14% ($258/kW)	42%	1,823	456	18,234
VERNON[3]	3.MW/4.5 MWh BES	32% ($305/kWh)	19% ($275/kW)	49%	1,416	944	4,250
METLAKATLA[4]	1 MW/1.2 MWh BES	-	-	-	-	-	1,200
SDG&E[5]	200 kW/400 kWh BES	16% ($658/kWh)	23% ($1,855/kW)	61%	8,150	4,075	1,630
PM250[6]	250 kW/167 kWh BES	20% ($449/kWh)	50% ($750/kW)	30%	1,500	2,245	375

1. The 20 MW/14 MWh BES was built in 1994/95 at a substation to provide spinning reserve and voltage regulation to the Puerto Rican electric grid.
2. The 10 MW/40 MWh BES was built at the Chino substation in Southern California in 1987/88 to provide spinning reserve and load leveling to the utility.
3. This 3 MW/4.5 MWh BES was built at a lead smelting factory in Vernon, California in 1995 to provide uninterrupted power to the factory.
4. The 1 MW/1.2 MWh BES was to provide voltage and frequency regulation, and to dampen demand spikes at a customer location in Metlakatla, Alaska.
5. The 200 kW/400 kWh San Diego trolley project was a demonstration project for transit system peak reduction application. 1991/92.
6. PM250 is the modular power management system product line developed by AC Battery Corp. Up to 50% cost reduction anticipated at a 40 MW/annum production volume.

Tables 5.2 and 5.3 list the costs of the battery subsystem of five BES projects. These tables include BEWAG, a German BES project undertaken in 1986, but excludes the Metlakatla project costs, as the project cost components for Metlakatla were not made available. These projects are similar because they all have large energy storage capabilities. However, their energy ratings are dependent on the discharge rate. The costs are listed in Table 5.2 in nominal dollars, and in 1995 dollars in Table 5.3.

Table 5.2: Cost of Batteries and Accessories

Name/Size of Plant	Nominal Cost ($ 000s)	Power Rating (MW)	Energy Rating (MWh)	Year of Installation
PREPA (Flooded)	4641	20	14	1994
CHINO (Flooded)	5967	10	40	1987/88
VERNON (VRLA)	1,375	3	4.5	1995
SDG&E (VRLA)	224	0.2	0.4	1991/92
BEWAG (Flooded)	4,300	8.5	8.5	1986

Table 5.3: Normalized Cost of Batteries and Accessories - 1995$

Name/Type of Plant	Cost in 1995$ ($ 000s)	Cost in 1995$ ($/kW)	Cost in 1995$ ($/kWh)
PREPA (Flooded)	4,780	239	341
CHINO (Flooded)	8,052	805	201
VERNON (VRLA)	1,375	458	305
SDG&E (VRLA)	263	1,315	658
BEWAG (Flooded)	6,015	707	707

The cost of each project listed in Table 5.2 in terms of $/kW and $/kWh must be examined together. Batteries with low power rating and high energy ratings will exhibit a very high $/kW cost and lower $/kWh cost. On the other hand, batteries in projects with large power needs for short durations will exhibit a low $/kW cost and high $/kWh cost.

Examining the per unit cost of batteries (in 1995$) in Table 5.3, the costs of the SDG&E and BEWAG project stand out. The VRLA batteries for SDG&E were supplied by Exide for peak shaving applications. They operated at 200 kW for 2 hours, to supply 400 kWh of energy (However, their rated 'nameplate' capacity was 827 kWh at a 6-hour rate). Such large variations in energy delivery capability for different discharge rates are typical for batteries.

The BEWAG project has a Hagen flooded lead-acid battery. The system operates either at 8.5 MW for an hour or at 17 MW for 20 minutes (the battery has a 14.2 MWh energy rating at a 5 hour discharge rate). The $707/kW and $707/kWh cost based on its 1-hour rating is higher than a comparable plant will now cost. The cost works out to $350/kW and $1,280/kWh based on its 20 minute rating. BEWAG was designed to provide spinning reserve and load-frequency control for the West Berlin 'island system' and is similar in operation to the PREPA project.

The PREPA, Chino and Vernon battery costs reflect today's cost. The PREPA battery, rated for < 1 hour of operation, has a highest $/kWh cost. Except for Chino, which has the biggest battery, the batteries have costs in the range of $300/kWh. The Chino battery is three times larger than PREPA and 9 times larger than Vernon, and appears to have benefited from economies of scale with a cost of $201/kWh. It should also be pointed out that PREPA and Chino are flooded lead-acid battery technologies, while Vernon is VRLA technology.

The battery cost for single digit MW/MWh-scale systems for durations of ~1 hour is ~$300/kW (or $300/kWh). Since these are installed costs, larger batteries will have lower per unit cost. Manufacturing economies of scale are not anticipated. It should also be borne in mind that project prices are generally negotiated.

The costs associated with batteries for the smaller 250kW/167 kWh PM250 unit developed by AC Battery Corp. is ~$450/kWh, well above the ~$300/kWh cost of the larger batteries. PM250 is the modular building block used to build larger BES systems. The PM250 unit at present costs ~$375,000, however, costs are estimated to decline by 50 percent at production volumes of 40 MW/annum, i.e., 160 units/annum.

5.2 POWER CONVERSION SYSTEMS

The rating of a power converter is limited by its ability to dissipate heat generated by the current it handles. It is rated in MVA. Assuming the power factor remains close to 1, the MVA and MW ratings are essentially the same. In general, the rating refers to the ability of the system to continuously handle the rated power. However, these systems have the ability to handle higher power (larger currents) for brief periods of time (in seconds). The Insulated Gate Bipolar Transistor (IGBT) and Gate Turn-off Thyristors (GTO) are the two main technologies used in power conversion systems.

The PCS costs of the five projects are tabulated below:

Table 5.4: Power Conversion System Costs

Name/Type of Plant	Nominal Cost ($ 000s)	Cost - 1995$ ($ 000s)	Cost - 1995$ ($/kW)
PREPA - 2x10MVA converter	5,713	5,884	294
CHINO - 10MVA converter	1,911	2,579	258
VERNON - 3x1MVA converter	825	825	275
SDG&E - 200kVA converter	316	371	1,855
BEWAG - 2x8.5 MVA converter	4,300	6,015	353

The cost of the 200 kW transistor-based PCS at SDG&E was very high, mainly due to over-engineering of the system. It was a self-commutated, IGBT-based voltage sourced PCS capable of 4-quadrant operation. The PCSs at Chino and PREPA, both supplied by GE, utilize self commutated GTO thyristor technology and are capable of 4-quadrant operation. The two 10 MW PCS supplied to PREPA were considered an improved version of the 10 MW PCS supplied to Chino. The higher cost of the PREPA unit does not seem to suggest a learning-curve cost reduction pattern. However, cost does seem to have decreased from that seen in the BEWAG units. The BEWAG PCS is a 2x8.5 MW line-commutated thyristor based unit.

PCS cost, primarily driven by its kW rating, seems to be in the region of $300/kW today. The three 1MW PCS at Vernon has a per unit cost of $275/kW. The PCS cost listed in Table 5.1 for the smaller 250kW/167kWh PM250 unit includes the cost of the converters, monitors and controls. It accounts for 50 percent of the unit cost, and is equivalent to ~$750/kW. At production volumes of 160 units/annum the total cost of the system is expected to come down by up to 50 percent.

The power converters in large energy BES systems and power converters in power quality systems are typically rated differently. Converters in power quality systems operate for durations in seconds, where as the large BES systems require a continuous rating.

Power electronics for BES power quality systems account for the largest portion of the cost, since the batteries in these systems are small (energy in tens of kWh). The PCS (power converter, controls, monitors and static switch) account for ~65 percent of the $989,000 PQ2000 system cost. This amounts to ~$300/kW for the 2 MW/10 second unit. The power converter itself will cost approximately half of the $300/kW price, with the static switch accounting for the balance of the cost.

5.3 BALANCE OF PLANT - SYSTEM INTEGRATION & FACILITY DEVELOPMENT

Balance of plant as discussed earlier encompasses the facility to house the equipment and interface between the ES systems and the customer/utility. In addition to buildings and interface equipment, the provision of such services as data gathering/trending, project management, transportation, permits, training, spares, finance charges, etc. account for approximately 50% of BES project costs, as illustrated in Table 5.1.

Expenditures associated with systems studies, design, project management and other related services account for up to 10 percent of the total cost. Finance charges (average funds used during construction) typically account for 5 percent of the system cost, while taxes account for approximately 5 percent. Taxes accounted for 8.25 percent of the Vernon plant cost. Transportation and packaging accounted for approximately another 5 percent.

Facility development cost is site specific. Among the plants investigated, it accounts for about 20 percent of the total project cost. Expenditures associated with site development, packaging, and transportation could be greatly reduced by transportable (housed in containers which can be mounted on trailers with ease) modular designs. Although such standardized modular design by integrators may not achieve an optimum match between the battery system and the utility requirements, the resulting cost savings may more than off-set the shortcomings resulting from the lack of optimal design.

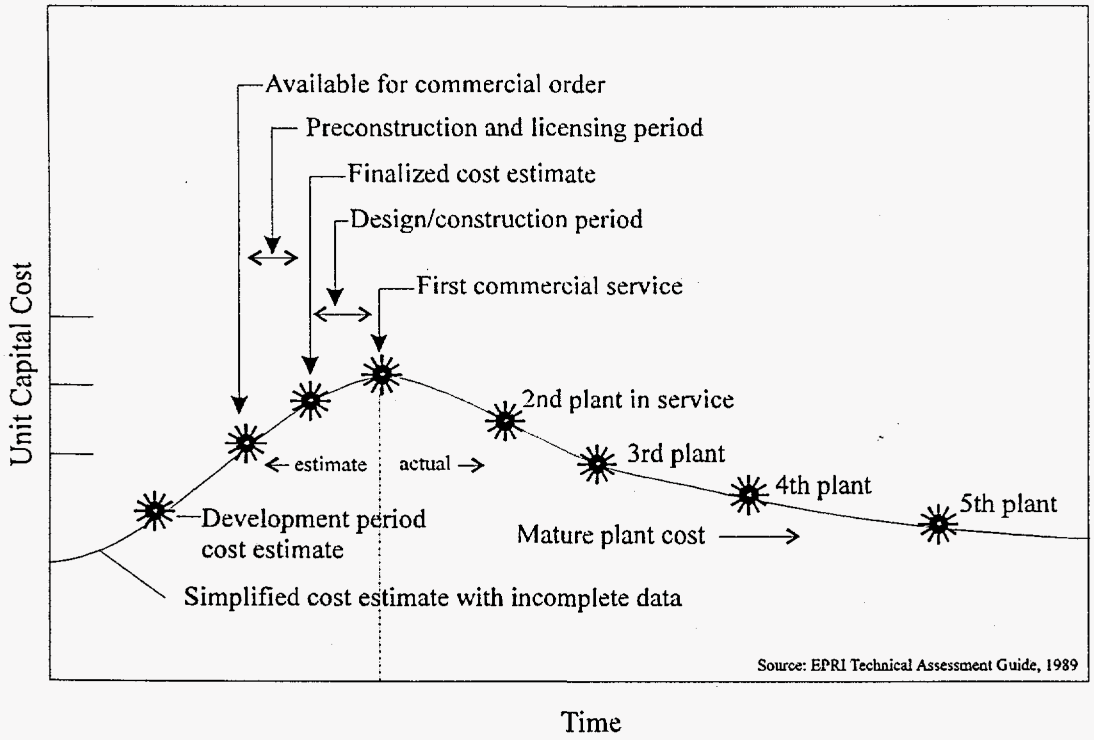
The trend towards having turn-key projects has the potential to drive costs down, since these in most instances are negotiated prices. In the case of Chino and PREPA, architectural and engineering firms were involved, and the projects were broken out to the lowest bidder of major components. Turn-key projects tends to have better coordination between different hardware suppliers, and tend to minimize integration and administrative costs. PREPA's planned second BES facility is expected to be built on a turn-key basis.

The balance of plant component costs of PM250 units is 30%. These are product costs, and not the total installed project cost seen by the end-use customer. Interconnections to customer facility, customer site preparation and other items are additional costs that may have to be borne by the customer.

5.4 COST REDUCTION POTENTIAL OF BATTERY ENERGY STORAGE SYSTEMS

A summary of component and system cost reduction potential is given in Table 5.5. Figure 5.1, obtained from the EPRI Technical Assessment Guide, illustrates the manner in which estimated and actual capital cost varies for new technologies.

Figure 5.1: Capital Cost Learning Curve



Source: EPRI Technical Assessment Guide, 1989

The storage technologies investigated in the report are at different stages of development. The large MW/MWh scale BES systems are now commercially available, but are designed on a one-of-a-kind basis. Though most of the building blocks that make up the system are off-the-shelf products, the system integration, construction of a building to house them, and transportation account for ~50 percent of the total project cost.

The total project cost of a BES system ranges between $1,200-1,500/kW for a 1-2 hour system (as seen in Table 5.1), depending on the site and application requirements. A cost reduction of up to 20 percent is projected by vendors, which consists of a 20 percent reduction in the cost of batteries, a 5-10 percent reduction in the PCS cost and a 10-15 percent reduction in the balance of plant costs. The cost of flooded lead-acid batteries at present is ~ $300/kW for a 1 hour battery.

The cost of power conversion and control subsystem for ES systems is on a downward trend, but substantial cost reductions (of GTO thyristor based PCS) are not anticipated by system developers. PCS developers predict that volume production provides the greatest potential for any cost reduction, but large markets to facilitate large production volumes are yet to emerge. IGBT based converters are low power devices (capable of handling lower voltage and current), however, many such converters can be connected in parallel to achieve the required power rating.

With IGBTs setting the trend in the power electronics industry, some PCS manufacturers are advancing the concept of modular PCS to bring the cost of PCS down. Modular PCS with lower power rating may be easier and cheaper to produce and may have wide scale applications (outside the energy storage market) and can be networked using software to achieve the same power rating of a single large converter. Production of large numbers of modular PCS units will benefit from the economies of mass production.

The PCS costs obtained for the projects includes the converter/controls themselves, but also includes many variable components such as the AC and DC switchgear, filters etc. At times the costs of monitoring and control equipment and software were not listed as separate cost items. They were presumably hidden in other cost items, probably under PCS cost. PCS costs of the larger energy units with continuous power ratings were found to be ~$300/kW. BES system developers expect this cost to drop 10-20 percent.

Table 5.5: Industry View of Present and Projected Cost of BES, SMES and FES Systems

ENERGY STORAGE SYSTEM	PRESENT COST	PROJECTED COST REDUCTION	INDUSTRY INPUTS	REMARKS
SUBSYSTEMS Flooded Lead-Acid Batteries	$300/kWh	5-10%	GNB, AC Battery, demos	Unit cost of batteries and accessories, specified in $/kWh are highly dependent on the rate of discharge. Cost specified is @ a 1-2 hour rate
VRLA	$300/kWh	5-10%	GNB, demos	Unit cost of batteries and accessories, specified in $/kWh are highly dependent on the rate of discharge. Cost specified is @ a 1-2 hour rate
Superconducting Magnet	$54,000/MJ	-	SI, B&W, IGC	Based on the planned 1,350 MJ (375 kWh) superconducting magnet for the Anchorage, projected to cost $20M. Large economies of scale seem to exist for larger superconducting magnets.
Flywheels	$200/kWh*	-	AFS, WFC, SatCon,literature	* $200/kW is direct cost estimate, based on a 1,000 kWh/100 kW system optimized for energy at a production volume of 2000 units(includes rotor, shaft/structure, motor/generator, bearing, cooling, vacuum assist, containment, system assembly/ installation). Energy component cost estimate of $800/kWh have also been made.
AC/DC Power Conversion Systems	$200-300/kW	25-40%	AC Battery, SI, demo	SI anticipates up to a 40% drop in its PCS costs, which at present cost ~300/kW based on power quality applications, with operating durations in seconds.
Static Transfer Switch	~$125/kW	25%	AC Battery	
Interface of ES system with External Supply	-	-	Demo	Very Site specific
Facility	$100 - 300/kWh	-	Demo	Site specific, partly dependent of size and type of energy storage medium
TOTAL SYSTEM BES - large storage applications	$1,200 - 1,500/kW for a 1-2 hr system	10-20%	Demonstration projects, GNB	The energy rating of large BES system is highly dependent on the application/discharge rate of the plant.
BES - power quality	~ $450/kW	20%	AC Battery	Projections for PQ2000. 2MW/10 second power quality system.
SMES - utility scale	$1,500/kW	N/A	B&W	The 30 MVA, 40 second unit for Anchorage is estimated to cost $44M. The utility is contributing $12.5M towards this demonstration project
SMES - power quality	$300-600/kW	30-40%	SI, IGC	A 8 MJ system costs $2.4 M. Could be used as a 8MVA system for 1 second dip protection or with a 2-3 MVA rating for 3 seconds.
FES - power quality	~$2,000/kW for a 2 hr system	-	SatCon, WFC	Is a 2kWh(7.2 MJ) flywheel rotor developed by SatCon. With a production volume in lower thousands, it is anticipated to cost $2,000 + installation, for a 1 kW/2 hr system.

6.0 CONCLUSIONS

There are mechanical, chemical, magnetic, and potential energy storage systems that can store electricity. Some of them, such as SMES and FES are being developed for very short term storage (from fractions of a power cycle to minutes), while systems such as pumped-hydro and compressed air are more suitable for long term storage (storage duration in hours to days). BES is considered to be appropriate for short to mid-term storage (from fraction of a power cycle to hours). Recent analysis as well as existing commercial scale BES projects, indicate that BES is more appropriate for electric energy storage for up to a few hours.

Electricity can be stored chemically as hydrogen. Though the hydrogen storage tanks (which determines the energy storage duration capability of the system) are inexpensive, the cost of the associated equipment becomes a significant component of the cost of the HES system for short duration storage. Hence, HES systems are more cost effective for applications that require long duration of storage, due to such system's lower cost (cost per unit of energy storage capability). Due to the potentially high capital cost of the system and relatively long system life, HES systems will also be most attractive for applications which require constant cycling.

Load leveling and 'firming' of intermittent renewable resources are applications requiring both long duration storage and frequent cycling. Pumped hydro and CAES can compete with HES for such applications, however, they are severely constrained by the lack of widespread availability of suitable sites. In contrast, modular HES systems can be installed even in urban settings, giving the HES systems many dynamic operating benefits that pumped hydro and CAES cannot claim. On the other hand, HES systems will not be able to compete with BES, SMES and FES systems in applications such as power quality and frequency control, since these applications require minimal storage and do not require constant cycling.

BES systems enjoy the modularity and sitting advantages like HES systems. This analysis shows that BES is more of a potential competitor to HES than any other storage system. The analysis further shows that HES systems are cost effective for applications which require storage durations of greater than 12 hours. Considering the cost reduction potential of the two system, with the systems costs of HES systems anticipated to come down faster than the BES system, the break-even storage duration drops to approximately 5 hours.

The report presents the capital cost data of commercial scale BES systems. This data provides a bench mark against which HES systems must be measured if they are to be commercially viable.

APPENDIX A: DESCRIPTION OF UTILITY APPLICATIONS OF ENERGY STORAGE SYSTEMS

3.1 Spinning Reserve

Spinning reserve is the generation capacity that a utility holds in reserve to prevent interruption of service to customers in the event of a failure of an operating generator. Typically this application requires 10-100 MW and < 30 minutes of storage, but storage capability of a few minutes is usually sufficient. The key to serving this application is quick response time, making BES, SMES and FES well suited for spinning reserve applications.

The BES plant in PREPA provides spinning reserve for the island electrical grid in Puerto Rico. The quick response time of the BES, enables the system to maintain a smaller spinning reserve capacity. This system, situated at the Sabana Llana substation in Puerto Rico, can simultaneously provide generation reserve during shortages, spinning reserve for system reliability, and voltage regulation. A 1,350 MJ (375kWh) system is being designed for spinning reserve/frequency support applications. It will be a 30 MVA, 40 second system, and will be tested at Anchorage Municipal Power & Light.

3.2 Generation Capacity Deferral

Generation capacity deferral is the ability of a utility to postpone the installation of new generating facilities by supplementing the existing facilities with another resource. This application requires 10-100 MW capacity for 2-4 hours. ES system for such applications does not exist and economics will not encourage it for the foreseeable future. HES system, with substantial cost reductions, may serve this application. Studies by the California Energy Commission estimate a levelized cost of such an application using BES system to be 13.3 cents/kWh[12].

3.3 Area/Frequency Control

Area/frequency control is the ability for grid-connected utilities to prevent the unplanned transfer of power between themselves and neighboring utilities, and the ability for isolated utilities to prevent the frequency of the electricity that they produce from deviating too far from 60 Hz. With deregulation, the transfer of power between utilities will be monitored more frequently than at present, and priced appropriately. Growth in this application is foreseeable, however, such applications using storage do not currently exist. BES, SMES and FES technologies are well suited to serve this application. HES is unlikely to serve this application due to its slow response characteristics.

3.4 Integration with Renewable Generation

Integration with renewable generation refers to the renewable power available during peak utility demand, and available at a consistent level. Power ratings up to 1 MW for 1-4 hours will be necessary to serve this application.

Batteries are being used with solar panels. Rural electrification has used central wind and solar energy facilities to charge batteries for use at homes. However, large grid-connected renewable

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[12] Energy Technology Status Report. Draft report 1996. Biennial report issued by the California Energy Comission which includes technology evaluations for more than 200 electric generation, storage, end-user and T&D technologies.

generation plants at present do not have storage capabilities. The economics of integrating renewable generation sources with storage systems is still under debate. High capital cost and energy consumption by the cryogenic and refrigeration systems in SMES systems might make them less suitable for long term storage. Application of flywheels for renewable applications is under consideration. HES, though under consideration for this application, due to its projected lower efficiencies (<50%) is unlikely to compete successfully in this application. However, if on-site electricity storage is required for very long duration (durations in days) hydrogen may provide a feasible option.

3.5 Load Leveling

The storage of inexpensive off-peak power for dispatch during relatively expensive on-peak hours is referred to as load leveling. This application will typically have a 100 MW rating for 1-4 hours. Economics at present will preclude the use of the BES, SMES and FES storage technologies, for reasons outlined in section 3.0, but HES may serve this application.

3.6 Transmission Line Stability

Transmission line stability is the ability to keep all components on a transmission line in sync and prevent system collapse. Ratings of 100+MW for durations in seconds is typical of this application. This application is suited for BES, SMES and FES storage technologies, but superconducting magnets, with their energy availability independent of the discharge rating, is especially attractive for this high power and short energy burst application. HES due to its sluggish response time is not suitable for this application.

Storage systems are suitable at instances when large load swings occur at customer locations, especially if the local network is weak to support such large swings. The BES at Metlakatla to support the large swings in the sawmill loads and FES at the Usibelli coal mine to support the drag-line loads are examples of such applications. The BES at Metlakatla has a 1MW/1.27MWh rating. The FES at the Usibelli coal mine is capable of storing 62.5 kWh at a top speed of 1,200 RPM. The motor/generator of the FES at this facility has a continuous rating of 1.8 MW and a 3 second rating of 5.2 MW. During drag line operation at the mine, the load swings as much as 3MW (peaking at ~6MW), but lasts for less than 8 seconds.

3.7 Voltage Regulation

The Opportunity Analysis Study defines voltage regulation as the ability to maintain the voltage at the generation and load ends of a transmission line within 5 percent of each other. This will typically require a 1MVAR rating for < 15 minutes. This application is suited for BES, SMES, and FES technologies, but not for HES systems. BES system at PREPA and SMES proposed in Anchorage are examples of such systems.

3.8 Transmission Facility Deferral

The ability of a utility to postpone installation of new transmission lines and transformers by supplementing an existing facility with another resource is referred to as transmission facility deferral. The capital cost of building storage systems with ratings of 10+ MW for 2-4 hours discourages storage systems for this applications. Situations may arise, however, where transmission bottlenecks may justify the capital cost of large storage systems. HES in these instances may become feasible.

3.9 Distribution Facility Deferral

Distribution facility deferral is the ability of a utility to postpone installation of new distribution lines and transformers by supplementing existing facilities with another resource. This application will typically require 1 MW of storage for 1-3 hours. A study by PG&E in 1994 concluded a 1MW-2 hour BES system with a 10 year life at $700/kW would enable the deferment of 1 substation increase per year. Commonwealth Edison is investigating the use of FES for the same applications, but with a smaller energy storage capacity.

3.10 Customer Service Peak Reduction

Customer service peak reduction is the storage of off-peak power for a customer to dispatch during the greatest on-peak demand as a method of reducing monthly demand charges. 100 kW-1 MW ratings for 1-2 hours are required for this application. Tariff structure at present makes it uneconomical to use storage systems for this application alone, despite large variations in prices within a given day.

With the introduction of real-time pricing, rates vary widely in any given day, providing the incentive to reduce demand during peak periods. The real-time tariffs in the Southern California Edison service territory are as high as $3.0/kWh between 2-4 pm on a hot summer day when temperatures exceed 95°F. The overnight tariff on the same hot day is 6.3 cents/kWh. Although the number of such 'hot' days are few in any given year, it illustrates the marginal system costs when the electrical system operates close to its capacity. Combining power quality applications with customer peak reduction may make storage attractive. Scenario in which inexpensive electricity is available seasonally, large HES systems may become feasible.

3.11 Transit System Peak Reduction

Transit system peak reduction is the storage of off-peak power for a transit system to dispatch during rush hour as a way to reduce monthly demand charges and to relieve the utility of a large demand burden. Storage system ratings in 1MW sizes for 1-2 hours are required. The SDG&E BES system was an example of a transit system peak reduction application. Future economics of the application are debatable; however, at locations where the local grid finds it difficult to support demand spikes at customer facilities, the use of storage may be an attractive option.

3.12 Reliability, Power Quality, Uninterruptible Power Supply - Small Customer

This application refers to the ability to prevent voltage spikes, voltage sags, and power outages that last for a few cycles (less than one second) to minutes, from causing data and production loss for customers with demands less than approximately 1 MW for durations in minutes. The application is attractive for storage systems. The economies of scale, however, due to the ancillary support equipment associated with SMES, makes SMES less attractive for applications with smaller power ratings (in the lower hundreds of kiloWatts). Small (1-100 kW/kWh) FES systems are becoming available in the market.

3.13 Reliability, Power Quality, Uninterruptible Power Supply - Large Customer

This application refers to the ability to prevent voltage spikes, voltage sags, and power outages that last for a few cycles (less than one second) to minutes, from causing data and production loss for customers with demands more than 1 MW for 1-2 hours. Power quality applications requiring storage durations in seconds are widespread. BES, SMES and FES systems are well suited for this application. PQ2000 and SSD examples of systems that are presently being commercialized.