Appendix A:

ENERGY STORAGE TECHNOLOGIES

OVERVIEW OF ENERGY STORAGE TECHNOLOGIES

Introduction

The U.S. electric utility industry is in the process of revolutionary change, from impending restructuring and competition, to limitations on installing new conventional generation and transmission and distribution equipment. The current situation in the electricity market may offer unique opportunities for energy storage technologies, particularly in combination with renewable energy generation, in which a few seconds to a few hours of electricity can be held for use at a later time [1,2]. These systems can be located near the generator, transmission line, distribution substation, or the consumer, depending on the application they are addressing.

Storage can play a flexible, multi-function role in the electricity supply network to manage resources effectively. As a generation resource, energy storage can provide savings in operating costs [3,4] or capital expenditures. Examples are: (a) spinning reserve for temporary generation backup, (b) frequency regulation for isolated utilities to maintain 60 Hz, and (c) capacity deferral of new generating facilities. In November 1994, the Puerto Rico Electric Power Authority installed a 20 MW/40-minute battery energy storage system for frequency and voltage regulation and spinning reserve [5]. The unit is dispatched just as any other generation resource in their system and the battery has reduced the impact of outages and improved reliability of electric service.

In combination with renewable resources, energy storage can increase the value of photovoltaic (PV) and wind-generated electricity, by making supply coincident with periods of peak consumer demand [6,7]. Energy storage may facilitate large-scale integration of intermittent renewable resources such as wind and solar onto the electric grid [8,9]. Energy storage systems complement renewable resources with siting flexibility and minimal environmental impacts.

Strategically-placed storage systems can increase the utilization of existing transmission and distribution (T&D) equipment and defer or eliminate the need for costly T&D additions [10-14]. Energy storage can be used to reduce the stress on individual transmission lines that are near peak rating by reducing substation peak load. Among specific T&D benefits are (a) transmission line stability for synchronous operation to prevent system collapse (b) voltage regulation for consistent voltage within 5% of set point, and (c) deferral of construction or upgrade of T&D lines, transformers, capacitor banks, and substations. Opportunities may develop for Independent System Operators to deploy storage to help balance regional loads as restructuring proceeds [1].

Energy storage can serve customers as a controllable demand-side management option that can also provide premium services, including (a) power quality for sags or surges lasting less than 5 seconds, (b) uninterruptible power supply for outages lasting about 10 minutes, and (c) peak demand reduction to reduce electricity bills.

A power quality problem is any voltage, current, or frequency deviation that results in the failure or misoperation of customer equipment. It can be a surge that lasts a few cycles (less than a second) or an outage that continues for hours, ongoing harmonic distortion or intermittent voltage flicker. A survey of 450 information systems executives at Fortune 1000 companies revealed that power quality problems resulted in significant computer crashes and productivity losses that are estimated to cost U.S. businesses $400 billion each year [15]. Power quality storage systems correct the problem in the first cycle and can be sized to provide a few seconds or minutes of protection.

Finally, energy storage is commonly used in stand-alone applications, where it can serve as an uninterruptible power supply (UPS) unit. UPS units are used for back-up power and only activate in cases of power outages unlike the energy storage systems discussed herein that perform a number of on-line applications. Isolated, remote locations, without connection to electricity grids, must consider some type of back-up power if an intermittent source is used. There are many examples of battery energy storage integrated with PV and wind facilities at national parks and military installations [8,9,16-19].

OVERVIEW OF ENERGY STORAGE TECHNOLOGIES

Electric Storage Technologies

A number of energy storage technologies have been developed or are under development for electric power applications, including:

- Pumped hydropower
- Compressed air energy storage (CAES)
- Batteries
- Flywheels
- Superconducting magnetic energy storage (SMES)
- Supercapacitors

Thermal energy storage technologies, such as molten salt, are not addressed in this appendix.

Pumped Hydro: Pumped hydro has been in use since 1929, making it the oldest of the central station energy storage technologies. In fact, until 1970 it was the only commercially available storage option for generation applications. Conventional pumped hydro facilities consist of two large reservoirs, one is located at base level and the other is situated at a different elevation. Water is pumped to the upper reservoir where it can be stored as potential energy. Upon demand, water is released back into the lower reservoir, passing through hydraulic turbines which generate electrical power as high as 1,000 MW. The barriers to increased use of this storage technology in the U.S. include high construction costs and long lead times as well as the geographic, geologic and environmental constraints associated with reservoir design. Currently, efforts aimed at increasing the use of pumped hydro storage are focused on the development of underground facilities [20].

Compressed Air Energy Storage (CAES): CAES plants use off-peak energy to compress and store air in an air-tight underground storage cavern. Upon demand, stored air is released from the cavern, heated and expanded through a combustion turbine to create electrical energy. In 1991, the first U.S. CAES facility was built in McIntosh, Alabama, by the Alabama Electric Cooperative and EPRI, and has a capacity rating of 110 MW. Currently, manufacturers can create CAES machinery for facilities ranging from 5 to 350 MW. EPRI has estimated that more than 85% of the U.S. has geological characteristics that will accommodate an underground CAES reservoir [21]. Studies have concluded that CAES is competitive with combustion turbines and combined-cycle units, even without attributing some of the unique benefits of energy storage [22].

Batteries: In recent years, much of the focus in the development of electric energy storage technology has been centered on battery storage devices. There are currently a wide variety of batteries available commercially and many more in the design phase. 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.

Flywheels: Flywheels are currently being used for a number of non-utility related applications. Recently, however, researchers have begun to explore utility energy storage applications. 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. A proper match between geometry and material characteristics influences optimal wheel design. As a result, engineers have focused on the development of materials with high working strength-to-density ratios. 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 [20,23].

Superconducting Magnetic Energy Storage (SMES): A SMES 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. The energy output of a SMES system is much less dependent on the discharge rate than batteries. SMES systems also have a high cycle life and, as a result, are suitable for applications that require constant, full cycling and a continuous mode of operation. Although research is being conducted on larger SMES systems in the range of 10 to 100 MW, recent focus has been on the smaller micro-SMES devices in the range of 1 to 10 MW. Micro-SMES devices are available commercially for power quality applications [20,22,23].

Advanced Electrochemical Capacitors: Supercapacitors (also known as ultracapacitors or supercapacitors) are in the earliest stages of development as an energy storage technology for electric utility applications. 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. Presently, very small supercapacitors 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 [24]. Currently, smal-scale power quality (<250 kW) is considered to be the most promising utility use for advanced capacitors.

Table 1 summarizes the key features of each energy storage system. Batteries, flywheels, SMES and advanced electrochemical capacitors lend themselves to distributed utility applications while pumped hydro and CAES are large, centralized installations. All cost estimates are for complete systems with power conditioning subsystems (PCS), controls, ventilation and cooling, facility, and other balance of plant components.

Research & Development

The Electric Power Research Institute, since its inception in 1972, has pioneered development of energy storage. Current programs are focusing on deployment of SMES, CAES, and batteries; and further assessments of the flywheels and super capacitors. The U.S. Department of Energy, through its Energy Storage Systems (ESS) Program, has focused almost exclusively on battery systems for the last decade for a variety of reasons, including technology versatility, applicability to customer needs, modular construction, and limited funds. Recently, the program has been expanded to include SMES, flywheels and advanced electrochemical capacitors. The ESS Program today performs collaborative research with industry on system integration and field testing, component development, and on systems analysis. Pumped hydro development was performed by the U.S. Army Corps of Engineers, flywheel development was done by the Department of Transportation, and SMES development was sponsored by the Department of Defense. Advanced electrochemical capacitors were investigated by the Department of Energy Defense Programs

Table 1. Energy storage technology profiles

Technology	Installed (U.S. total)	Facility Size Range	Potential/Actual Applications	Commercially Available	Selected Manufacturers	Estimated System Costs ($1997)
Pumped Hydro	22 GW at 150 facilities in 19 states	Up to 2.1 GW	Electricity • Load Leveling • Spinning Reserve	Yes	Allis-Chalmers, Combustion Engineering, General Electric, North American Hydro, Westinghouse	500-1,600 $/kW
CAES	110 MW in Alabama	25 MW to 350 MW	Electricity • Peak Shaving • T&D Applications • Spinning Reserve	Yes	Dresser Rand, Westinghouse, ABB	350-500 $/kW (commercial plant estimates)
Batteries	More than 70 MW installed by utilities in 10 states	From 100 W to 20 MW	Electricity • Spinning Reserve • Integration with Renewables • T&D Applications • Power Quality (PQ) • Peak Shaving Transportation	Yes (Flooded Lead-Acid, VRLA) No (Zinc/Bromine, Lithium)	AC Battery Corp, C&D, Delco-Remy, Delphi , GE Drive Systems, GNB, Precise Power Corp., SAFT America, Yuasa-Exide, ZBB	750-1,000 $/kW (20-40 MW, 2 hrs) 500-600 $/kW (20-40 MW, 0.5 hr) 400-600 $/kW (2 MW, 10-20 sec)
Flywheels	1-2 demo facilities, no commercial facilities	kW-scale	Electricity • Power Quality Transportation Defense	Yes (steel, low rpm) No (advanced composite)	American Flywheel Systems, Boeing, Int'l Computer Products, SatCon, US Flywheel Systems	Advanced: 6,000 $/kW (~1 kW) 3,000 $/kW (~20 kW) Steel: 500 $/kW (1 MW, 15 sec)
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)	Superconductivity, Inc.	1,000 $/kW (1-2 MW, 1 sec)
Advanced Electrochemical Capacitors	Millions of units for standby power; 1 defense unit	7-10 W commercial 10-20 kW prototype	Electricity • Power Quality Consumer Electronics Transportation Defense	Yes (low-voltage, standby power) No (power quality)	Evans, Maxwell, NEC, Panasonic, Pinnacle, Polystor, Sony	unknown

Sources: References 1, 20, 22-25

and Office of Transportation Technologies, although it appears that only defense applications are currently being pursued.

This report is focused on renewable energy generation technologies. The most appropriate storage systems for such applications presently appear to be batteries. Batteries have been installed in stand-alone PV and wind systems for more than two decades throughout the U.S. Worldwide sales of batteries attached to PV installations in 1995 were estimated at 3,000 MWh, with total installed of over 10,500 MWh. U.S. sales of PV batteries in 1995 were estimated at 340.5 MWh [26]. These annual sales statistics include both new installations and replacements. They are significant when considered against the amount of PV generating capacity in operation. By 1996, the U.S. PV industry had installed a total of 210 MW of PV generating capacity worldwide [16].

Batteries support renewable generation in at least three size ranges: (a) 1-4 kW residential, (b) 30-100 kW commercial, industrial, or village, and (c) > 1 MW generation or grid-support. Much of the activity funded by the PV industry has focused on residential-scale applications with oversized (many hours of) battery back-up, while much of the activity funded by the battery manufacturers has focused on the industrial-scale applications with low battery back-up. For example, EPRI and Sandia National Laboratories are completing an analysis of a 2.4 kW PV array and 7-hour battery operating in a grid-connected home in the Salt River Project service area [8].

Opportunities for PV are appearing in geographic zones previously excluded from consideration. The National Renewable Energy Laboratory (NREL), assisted by the State University of New York (SUNY) at Albany, has derived a new measure of effective PV capacity. The effective load-carrying capacity is the ability of any generator to effectively contribute to a utility's capacity to meet its load. While the intensity of solar insolation is critical to PV, it is less important than PV's relationship to load requirements [9]. SUNY researchers have developed a complementary measure of the minimum amount of back-up or stored energy needed to ensure that all utility loads above a threshold are met by the PV/storage system. The minimum buffer energy storage measure found that a small amount of storage could yield an increased capacity credit for PV.

The following technology characterization proceeds from the SUNY premise, examining an integrated 30 kW PV/30 kWh battery system connected to the electric grid.

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