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ENERGY STORAGE FOR A COMPETITIVE POWER MARKET

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ABSTRACT

This article discusses briefly the status of energy storage technologies and explores opportunities for their application in the rapidly changing US energy marketplace. Traditionally, electric utility energy storage has been used to store low-priced purchased or generated electric energy for later sale or use when energy cost would otherwise be much higher. But deregulation and restructuring in the electric industry, coupled with an expanding portfolio of storage alternatives, may lead to many new opportunities for energy storage, especially within the energy distribution infrastructure, and for maintaining or providing power quality at large customer sites. Small, modular, robust energy storage technologies could be used to solve a range of energy supply and infrastructure-related needs. This article provides quantitative evidence of utility-related energy storage status, benefits, and opportunities.

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INTRODUCTION

Stored energy has been used by the electric utility industry for over a century in the central energy supply system. Such energy is used primarily for "load leveling," i.e. to store low-cost (or low-priced) electric energy and to sell or use that energy when the real-time electricity generation cost or purchase price is high. Load-leveling has been accomplished using large pumped hydroelectric plants that pump water into an elevated reservoir to store the energy. The stored water's potential energy is used later to produce electricity with conventional hydroelectric generation equipment. Electrochemical batteries have also had a place in electric utilities, most often in support of substation equipment.

The use of energy storage has not expanded significantly beyond these applications for two reasons: 1. The price of primary energy sources, mostly fossil fuel, has kept electric energy costs low, and continuous improvements in generation equipment have meant declining costs for electric power capacity, allowing for cost-effective electricity production as needed and limiting the benefits of storing energy. 2. Generation technologies are familiar to operators, and their dispatch is more straightforward than that for storage technologies, which have time-dependent features. As a result, utility planners have been slow to implement new energy storage strategies.

With utility restructuring, the role of energy storage is expected to move from the central supply system into more distributed or local applications. This opportunity arises in part because storage technology has become more modular and in part because different entities will operate the generation, transmission, distribution, and end-use pieces of the business, and each can use storage to its advantage to meet customer needs and maximize return on investment.

Energy storage offers additional benefits in utility settings because it can decouple demand from supply, thereby allowing increased asset utilization, facilitating penetration of renewables, and improving the flexibility, reliability, and efficiency of the electrical network. Energy storage can give utilities an unprecedented capability to manage their energy production resources and their power capacity.

Several storage technologies are either available or in an advanced state of development. Because all energy storage systems consist of an energy "reservoir" subsystem (measured in MJ or MWh of storage) and a power delivery subsystem (rated in MW of capacity), the value of use can result from available energy in the storage reservoir or from speed or flexibility in providing power. System size ranges from very small—1 MJ (= 0.00028 MWh)/1 MW—to very large—10,000 MWh/3000 MW.

This paper focuses on energy storage technologies that couple directly into the electrical utility system. Electrical, mechanical, and thermal storage systems are discussed; gaseous storage (i.e. natural gas and hydrogen) is not included. Also, because the restructuring opportunity presented is a US domestic target, the focus is on domestic projects. Significant international opportunities also exist for the use of energy storage, but these are not documented here. This paper is based in part on the results of a US Department of Energy (DOE) Workshop ("The Emerging Roles of Energy Storage in a Competitive Power Market") held in December, 1994 (1).

This paper reviews briefly the status of energy storage technologies and presents in chronological order the historical, current, and future uses and benefits of energy storage within the electric utility sector. Recommendations for technology and analysis developments that could accelerate commercial application of energy storage are summarized.

STORAGE TECHNOLOGY STATUS

Most energy storage systems convert utility alternating current (ac) power to a form of stored energy and convert it back to utility-grade power when needed. Each type of conversion requires a storage subsystem and a power conversion system (PCS). The power rating and desired duration of discharge determine the storage capacity required. A summary comparison of the various electrical and mechanical storage technologies is provided in Table 1. Thermal energy storage is discussed separately at the end of this section.

In the past decade, available energy storage technologies have changed dramatically—from new modular pumped hydro with reservoirs that have less environmental impact than earlier concepts, to supercapacitors, evolutionary batteries, superconducting magnetic energy storage (SMES), flywheels, and compressed air energy storage (CAES). These technologies have been nurtured by different industry sectors for various applications including electric utilities, transportation, and the military. In the United States, significant research and development has been supported by the US DOE and Department of Defense,

Table 1 Comparison of energy storage characteristics

	Flywheels	Batteries	Pumped hydro	CAES[a]	Micro SMES	SMES[b]	Capacitors
Efficiency	~90%	~75%	~75%	~70%+ fuel	~95%	~95%	~90%
Energy range	1 MJ–5 MWh	0.5–50 MWh	0.5–10 GHw	50–5,000 MWh	1–500 MJ	0.5–1,500 MWh	1–10 MJ
Power range	1–10 MW	0.5–100 MW	0.5–3 GW	0.1–1 GW	1–30 MW	10–1,000 MW	1–10 MW
Modular	Yes	Yes	No	No	Yes	Possible	Yes
Cycle life	10,000	2,000	10,000	10,000	10,000	10,000	10,000
Charge time	Minutes	Hours	Hours	Hours	Seconds–minutes	Minutes–hours	Seconds
Siting ease	Good	Moderate	Poor	Poor	Good	Poor	Easy
Storage measure	Easy	Poor	Easy	Easy	Easy	Easy	
Lead time	Weeks	Months	Years	Years	Weeks	Years	Weeks
Environmental impact	Benign	Moderate	Large	Large	Small	Moderate	Small
Environmental control	None	Some	Some	Required	Small	Some	None
Risk	Small	Moderate	Moderate	Moderate	Small	Moderate	Small
Thermal requirement	LN2[c]	Air conditioning	None	Cooling	LHe[d]	LHe	None
Maturity	Under develop-ment	Mature	Mature	Available	Available	Under develop-ment	Available

[a]Compressed air energy storage.
[b]Superconducting magnetic energy storage.
[c]Liquid nitrogen.
[d]Liquid helium.

the Electric Power Research Institute (EPRI), the electric utilities, and vendors. Developments from abroad have also been incorporated into today's technology. This section describes briefly the available technologies. Interested readers may find more information in the cited literature.

Pumped Hydro

In pumped hydro storage, a body of water at a relatively high elevation represents potential or stored energy. Electrical energy is produced by releasing the water so that it drops to a lower elevation where it flows through hydroturbines into a reservoir. The water is pumped back up to recharge the upper reservoir and to allow the cycle to be repeated. Generation and pumping can be accomplished either by single-unit, reversible pump-turbines or by separate pumps and turbines. The switch between pumping and generating can occur within minutes; depending on the installation, such changes occur from once or twice to more than 40 times daily.

Pumped hydro is a mature technology, with about 300 systems operating worldwide. Their capacities range from 20–2100 MW. Round-trip energy conversion efficiency has improved recently to nearly 80%. Further improvements resulting from the use of adjustable speed drives for the pumps are anticipated. Siting flexibility is now possible because underground storage can be used for both the upper and lower reservoirs (2). Unit prices for pumps/turbines have leveled out in recent years as the technology has matured; increased system costs can be attributed to the use of more sophisticated electronic controls.

Batteries

Energy storage batteries store energy in electrochemical form in "cells" by creating electrically charged ions. The chemical energy is converted back into a flow of electrons in direct current (dc) form, which must be converted with power conditioning equipment to ac, when the energy is used in conjunction with the electric grid. Because of the electrochemical nature of the conversion, battery operation is subject to several limits. One is cycle life, which is the number of charge/discharge cycles possible for a given cell. Another is depth-of-discharge, which is the fraction of stored energy that can be withdrawn; this depends on the rate of discharge and impacts the cycle life. These and other issues, such as the effect of temperature, are discussed in (3). The status of the battery cell types most applicable to electric service applications is indicated in Table 2 (4). (Note: Metal hydride and other advanced batteries are not available in utility sizes.)

Battery cell technology, especially lead-acid, is relatively mature, but stationary battery systems are not. Systems in regular operation are located at the Chino substation (10 MW/40 MWh) on the Southern California Edison

Table 2 Characteristics of battery types for utility energy storage

	Status	Cell cost ($/kWh)	Footprint[a]
Wet lead-acid	Available	100	Large
Valve regulated	Available	200	Medium
Zinc/bromine	Commercial prototypes	150 50 (2nd)	Small
Sodium/sulfur	Commercial prototypes	∼200 (mature)	Small

[a]Footprint is the floor area covered by the device.

system, on the Crescent Electric Co-op system (500 kW) in South Carolina, on the Puerto Rico Electric Power Authority system (20 MW/14 MWh), and on the Berlin Electric Utility system. System costs need to be reduced. Reductions resulting from optimized integration, mass production, and the use of advanced batteries to improve cycle life are anticipated (5). The electric vehicle market will help advance battery technology and commercialization for utility applications. Progress has been made in making batteries recyclable, but some depleted materials are considered hazardous waste, which means disposal options for these materials are limited and disposal costs are higher.

Superconducting Magnetic Energy Storage

In Superconducting Magnetic Energy Storage (SMES), energy is stored in the magnetic field produced by dc current circulating through a superconducting coil. SMES is an attractive option because there are no resistive losses in the superconducting coil and losses in the solid state power conditioning are minimal. Like a battery, a SMES system provides rapid response for either charge or discharge. Unlike a battery, the amount of energy available is independent of the discharge rating. The interaction of the circulating current with the magnetic field produces large magnetic forces on the conductor. In a small magnet, these forces are easily carried by the conductor itself. In a large magnet, a support structure must be provided, either within the coil windings or external to the coil, to carry these larger loads. SMES coils are configured in two general ways (with some variations). A solenoidal coil has the minimum cost of superconductor and coil components; however, it produces a stray magnetic field that decreases with the inverse cube of the distance from the coil. A toroidal coil has a minimal external magnetic field at the expense of additional superconductor and winding materials. SMES costs are therefore highly dependent on size and magnet configuration. For this reason, these costs are not well established. Safety concerns about SMES have been addressed through the design of quench detection and protection systems that dissipate the stored energy resistively, either internally or externally (6).

SMES has been demonstrated at the 30 MJ size (on the Bonneville Power Administration system in 1985), and more recently it has been made commercially available by Superconductivity, Inc. (SI) in a 3 MJ/1.4 MW size (7). SI "microSMES" units are being sold and leased in the United States, and 10 are scheduled for shipment to ESKOM, the national utility of South Africa. Intermagnetics General has recently been awarded a contract by the US Air Force for a 6 MJ unit. A 0.5 MWh/30 MW system is being designed by Babcock and Wilcox for the Anchorage Municipal Light and Power system; cofunding is being provided by the Advanced Research Project Agency through the Technology Reinvestment Project.

Compressed Air Energy Storage (CAES)

CAES systems store energy (charging) by compressing air within an air reservoir, using a compressor powered by off-peak/low-cost electric energy. A special clutch is required to allow the turbine/generator to operate in two directions, one for charging and one for discharging. Three reservoir types are generally considered: naturally occurring aquifers (such as those used for natural gas storage), solution-mined salt caverns, and mechanically formed reservoirs in rock formations. Aquifer storage is by far the most cost effective.

During charging, the plant's generator operates in reverse—as a motor—to provide mechanical energy needed by compressors, which send compressed air into the reservoir. When the plant discharges, it uses the compressed air to operate its combustion turbine. Natural gas is also burned during plant discharge, in the same way it is burned during gas generation in a conventional combustion turbine plant. The turbine turns the generator, which creates electricity.

The first US CAES plant, completed in 1991, is currently operated by the Alabama Electric Co-op. This plant has a power rating of 110 MW and a storage capacity of 26 h (8). A 220 MW plant has been operating at Huntorf, Germany since 1978. Many potential sites for CAES are available in the United States. Where sites are available, CAES appears to be the most economic multi-MW storage option for systems that require from 3–12 h of storage per day, because of the low marginal cost of storage. Smaller CAES systems using small, modular, efficient aero-derivative combustion turbines may be possible for on-site applications for a large industrial user or independent power producer.

Flywheel Energy Storage

Flywheels, which store kinetic energy in a rotating mass, have typically been used as short-term energy storage devices for propulsion applications such as powering train engines and road vehicles, and in centrifuges. In these applications, the flywheel smooths the power load during deceleration by dynamic braking action and then provides a boost during acceleration. Appropriate electric utility applications of flywheels are related to the operation of motor/generator, such as those driven by a gas or steam turbine, and include load leveling and buffering of momentary outages. Because the rotational speed (frequency) of the flywheel will change as energy is charged or discharged from the device, energy must be transmitted into and out of the flywheel system via a variable frequency cyclo-converter. The design of the converter is highly dependent on the size and application of the flywheel system. Several are described in (9).

New high strength composite materials are the key to the new class of flywheels, but reliable and inexpensive bearings continue to be the major hurdle.

Many of the emerging flywheels use superconducting bearings that are magnetically levitated to reduce bearing friction and drag losses (10). Development of flywheels for electric vehicles should help advance the state of the art. Power conditioning system costs dominate system costs for power quality applications and are dependent on the flywheel design because of the interaction between the flywheel circuitry and converter (11). Small, high-speed flywheels (also called electro- mechanical batteries or EMB) are becoming commercially available from Trinity Flywheel of San Francisco. The Boeing Company is currently marketing a 1 MWh flywheel for utility load management applications.

Capacitors

Capacitors store energy as electric charge between two plates—metal or conductive—separated by an insulating material known as a dielectric when a voltage differential is applied across the plates. The factors that determine the capacitance are the size of the plates, the separation of the plates, and the type of material used for the dielectric.

Capacitors are already used in many utility power control applications. The advantages of capacitors for small energy storage and short discharge are long cycle life and immediate recharge capability. A capacitor's energy density is low, however, so only small units are realistic. Recent advances in "supercapacitor" technologies are notable because of the huge increases in energy density attained over conventional capacitors (12). The advances are a result of the choice and preparation of electrode materials and huge increases in the effective capacitive plate surface area. These improvements move some capacitor applications up to the 1–5 MJ range.

Energy Storage System Costs

Capital and operating costs for the electrical energy storage systems discussed above are listed in Table 3. These values are the most recent available and are based on the compilation found in (1). For any system, the capital costs of the storage system ($/kWh) and power conversion system ($/kW) are added. For most of the projected future applications (discussed in later sections), technologies should be compared on a capital-cost basis. For load-leveling applications, a life cycle cost analysis (i.e. revenue requirement in ¢/kWh) is appropriate. The results of such a comparison depend greatly on the size of the storage unit, the hours per day of operation, and the user/owner's economic or financial parameters. In a recent study (13), such a comparison showed CAES and pumped hydro to be particularly attractive for very large-scale applications.

Table 3 Energy storage cost comparison

	Flywheels	Batteries	Pumped hydro	CAES	Micro SMES	SMES	Capacitors
Energy capital cost ($/kWh)	100–800	200	~15	10	300 $/MJ	3000	3600 $/MJ
Power capital cost ($/kW)	220	300	600	425	500	300	300
Operating cost (fixed) ($/kW/yr)	7.5	1.55	4.3	1.35	8	1	5% of capital cost
Variable (¢/kWh)	0.4	0.5	0.43	0.1	0.5	0.1	~0

Thermal Energy Storage

Fifty percent of all energy used is in thermal form, 50% of electricity is used for thermal energy needs, and about 90% of power generation is accomplished with thermal processes. Therefore, it is logical to seek better ways to optimize recovery, transport, conversion, and use of thermal energy for process, power generation, and space heating applications by using state-of-the-art and emerging thermal energy storage technologies.

Thermal energy storage (TES) systems store thermal energy—hot and/or cold—in a reservoir containing thermal mass. Cold storage is used for facility cooling (air conditioning) and heat storage is used for facility heating or industrial processes or power generation (14). Thermal energy is stored as sensible heat or as latent heat involving material phase change (most often from liquid to solid for cold storage and from solid to liquid or liquid to vapor for heat storage). Most cold TES systems use water (ice or liquid), salt-water brine (eutectic salts), or antifreeze materials. Systems storing heat primarily use water or eutectic salts. Geothermal reservoirs and water aquifers are particularly well suited to heat pump applications.

TES equipment for cold storage is integrated into a facility's heating, ventilating, and cooling (HVAC) system (15). Energy is stored when electric power demand and costs are low, and it is used during peak-demand/high energy–cost periods. TES has also been proposed for power plant cooling that can boost output 15–20% when the ambient temperature and humidity are high.

Stored heat is most often used for domestic or other hot water needs. It has been in use in homes in the United Kingdom for 25 years as a consequence of time-of-day pricing. Stored heat systems (most use oil/rock reservoirs) have been analyzed and proposed for power plant applications (16) where significant efficiency improvements appear possible.

TES is a viable, cost-effective, proven energy storage option for a growing number of locations and applications. TES is often justified based on infrastructure cost avoided and on energy-use and demand-cost implications. To generalize about cost, benefits, and performance is difficult because these factors vary considerably with site, application, system, and load, but a methodology has been suggested in (17). The key impediments to more use of TES are the perception of relatively high technical risk with less emphasis on financial risk, relative unfamiliarity to facility designers, and relatively high incremental up-front costs.

CURRENT ENERGY STORAGE APPLICATIONS AND BENEFITS

Traditional Use and Current Applications of Energy Storage

Until recently, electric utilities have had relatively well-defined objectives and customers, and hence, business and technology strategies. For vertically integrated utilities (i.e. those containing generation, transmission, and distribution functions), the apparently ever-increasing economies of scale of central generation led to a "grow and build" strategy. This encouraged utilities to pursue more market aggregation and allowed utilities to build new plants that were notably larger and more efficient than those of prior years. Distribution companies would encourage their cooperative suppliers to build larger, more efficient plants to lower fuel costs and provide more reserve margin.

Historically, utilities knew who their customers would be and what they expected (low-cost energy and sufficient power reserves), and they knew how to make investments and how to operate the system to ensure profitability. Most important, however, was the fact that each utility had the information necessary to make prudent investment decisions to carry out that strategy. In some cases, utilities had the opportunity (and recognized its value) to add bulk storage to their systems. The original, somewhat limited storage strategy was to (*a*) be able to store hydro-power for more opportune times, (*b*) buy low and sell high for electric power generation, and (*c*) allow better asset utilization for their peaking and intermediate-duty cycle generating plants.

Some energy storage is used for load leveling as part of electric utilities' central electric supply system. Pumped storage plants are often developed in conjunction with specific long-term bulk energy purchase agreements or to complement specific large baseload power plants (i.e. plants that cannot be switched on and off easily and that produce power most of the time, even at night when demand for electricity is low). Duke Power commissioned the four-unit 1065-MW Bad Creek, North Carolina project in 1991 and 1992 (18). A 2000-MW project at Mt. Hope in northern New Jersey is in the planning stages (2).

Electric utilities use small amounts of energy storage for capacity benefits. Batteries at power plants provide black-start capability (power for plants that need electricity to start up). In a few cases, batteries have been installed at or near overloaded power distribution substations. Technically, capacitors used by utilities to stabilize electricity quality (voltage and current) are energy storage devices, but they only store and discharge very small amounts of energy. As part of their demand-side management (DSM) programs, some electric utilities have encouraged customer use of thermal energy storage in order to use electricity during periods of low demand (i.e. when use of the electricity infrastructure capacity is low) to make ice. The ice is used during the day, presumably during times of peak electric demand, for cooling.

In recent years, several facilities using the newer energy storage technologies (CAES, batteries, and SMES) have been built in the United States for specific purposes. The Alabama Electric Co-op 110-MW CAES plant, for example, has allowed the deferral of new generation (8).

In the late 1980s, EPRI, Southern California Edison Company (SCE), and the International Lead/Zinc Research Organization (ILZRO) sponsored a “utility-scale,” grid-interactive, lead-acid battery energy storage system demonstration at Chino, California. The 10-MW plant has a storage capacity of 4 h (40 MWh). The plant operated as a demonstration from 1986–1988; in 1991, it began operation as an actual utility resource, dispatched primarily for central supply related benefits.

SCE’s and EPRI’s primary objective was to learn about operation of a utility grid–connected battery system and to examine methods of optimizing grid operations using battery systems (19). The plant exhibits excellent availability and reliability. Operational benefits demonstrated include transmission and distribution (T&D) deferral, load leveling, frequency regulation, volt-amp reactive power (VAR) support, local reliability, and black-start operation.

In 1992, Central Hudson Gas and Electric Company sponsored installation and testing of a small SMES unit (1 MW, 0.75 MJ) at a customer’s site, as a way to improve local power quality and reliability (20). The customer was IBM, and the facility produced semiconductor products. Somewhat frequent, short power quality anomalies were causing significant productivity losses in the plant. The SMES device from Superconductivity, Inc. was designed and installed in less than one year. During the device’s first 15 months of operation it provided 46 carryovers. Through 1994, it operated reliably and provided acceptable, cost-effective performance.

Benefits and Economic Value of Energy Storage in Current Utility Roles

In addition to the buy-low/sell-high benefits from load leveling, energy storage can, depending on its application, provide additional benefits. These capacity and operational benefits accrue if utilities can use storage in any of the following roles: (*a*) to minimize the need for new electricity capacity, in order to reduce system cost; (*b*) to improve economic utilization of and/or environmental performance of existing electric capacity; (*c*) to increase revenues and reduce emissions; or (*d*) to provide flexibility for planning and operations.

According to various sources, benefits of energy storage, when added together, can approach \$1000/kW (21, 22). Descriptions and estimates for individual benefits are reported in this section.

CAPACITY BENEFITS Capacity benefits accrue when energy storage allows utilities to defer or avoid otherwise needed additions of central peaking generation capacity, central transmission, or local transmission. Capacity benefits are calculated as the present worth of deferring or totally avoiding costs for infrastructure additions and enhancements that would otherwise be needed. An example is electric utility programs that encourage customer use of TES for cooling, mostly to defer the need for central generation capacity by limiting peak demand for air conditioning. The utility can avoid building a new power plant costing \$1000/kW by partnering with 100 large customers to install TES systems.

Generation capacity benefits may range from none for utilities, which already have sufficient reserves of generation and supply capacity, to \$500–\$600/kW for utilities that are about to add electric supply resources (23, 24).

Transmission capacity benefits are also becoming very important as load centers grow and environmental concerns limit the construction of new transmission. If energy storage can relieve loading on transmission lines by storing energy during off-peak hours, expensive transmission upgrades may be avoided. In addition, any excess on-peak transmission capacity freed up by such load shifting may be sold to wholesale power producers selling power to remote customers. The transmission capacity benefits of energy storage vary considerably, depending on the types of upgrades and the distance of the lines involved. Gross estimates are, based on cost for transmission capacity, that the value can approach \$200/kW for utilities with an imminent need for transmission capacity (23).

DYNAMIC OPERATING BENEFITS A significant amount of benefit can be achieved by using energy storage to optimize several important aspects of utility electric supply system operation (25). These dynamic operating benefits include the following:

1. Load following. Electric supply capacity is provided as needed, to meet minute-to-minute variations in electric demand. Load following is normally provided by generation resources at substantial cost. Energy storage can often provide more efficient load following than generation resources because most types can change power output levels rapidly (i.e. they have rapid "ramp rates") and have relatively good efficiency at part load operation.

2. Spinning reserve. Closely related to load following, spinning reserve is generation capacity held in reserve for use if other electric supply resources become unavailable unexpectedly. Usually spinning reserve is provided by operating several large plants at power output levels well below their maximum so that there is margin available. Energy storage technologies with rapid ramp rates can often provide spinning reserve; credit is given for the reserve even if the unit is never discharged. In addition, if energy storage plants are being charged, they get a double credit for spinning reserve capacity: one credit for the storage unit's charging load, which can be turned off, and a second credit for the actual capacity the storage can provide.

3. Frequency, voltage, and power factor correction. Maintaining consistency, quality, and reliability of power transmitted within a utility's system is important. In many cases, these elements can be provided by energy storage whose output can respond very rapidly, such as batteries and SMES, and CAES operating at part load. Frequency and power factor (i.e. phase angle) control also require that the power conditioning system of the storage plant have four-quadrant control, which means "real" power flow control and "reactive" phase-angle control.

4. Commitment of generation power plants. Commitment refers to the process of staffing and starting up a thermal generation plant, often several hours ahead of time, so it is available when needed, to meet demand for power as it increases. If it can meet demand for power, a charged storage plant may allow power system operators to delay or avoid power plant commitment entirely, thus saving staffing and fuel costs. This also reduces wear and tear on equipment and thus extends the generation equipment's useful life, increases availability and reliability, and extends maintenance periods.

5. Environmental impacts. Energy storage may allow utilities to avoid start-up or operation of fossil power plants at part load, thus reducing fuel use and air emissions (per kWh generated). Power plants are operated at part load if they are (*a*) actively following minute-to-minute load variations, (*b*) providing spinning reserve, or (*c*) ramping up to meet loads as they grow during the

day. Other environmental benefits accrue if energy storage enables the use of nonpolluting renewable energy sources (26).

6. Black-start of fossil/thermal plants. Energy storage may provide electric energy needed to start up power plants, if power is not available from the grid or from other generators. This application requires sophisticated power control devices, such as gate turn-off thyristors (GTOs)—advanced solid state devices that allow power flow in either direction.

The values of dynamic operating benefits are difficult to estimate for several reasons. One is that appropriate analysis tools are just now being developed. Another is that necessary time-dependent data and historical operating and maintenance (O&M) data are costly or unavailable. Also, in many cases, energy storage often must be compared to the most likely alternative, to determine the relative benefit value, because some types of generation can also provide many of the same benefits. Also, dynamic operating benefits overlap. Thus, the evaluation of dynamic operating benefits requires use of dynamic models, such as chronological production cost models, with uncertainty and scenario evaluation capabilities.

TACTICAL AND STRATEGIC BENEFITS To the extent that storage provides utilities with a more flexible, more robust way to respond to a variety of conditions, system operation can be more efficacious, optimized to a greater extent, and more responsive to changes, presumably with lower cost and lower risk. Electric system operators and planners can utilize this flexibility to develop and implement lower cost, more optimal responses to changing business conditions.

Recent research by EPRI indicates that energy storage can reduce uncertainty in providing energy supply such that the overall value of storage is 40% higher than generation alternatives (27). Electric supply planners and negotiators may be able to utilize the combination of attributes unique to energy storage to secure long-term power purchase agreements with more favorable terms. Modular energy storage technologies allow utilities to add relatively small, more optimal capacity increments, with relatively short lead times, and to defer otherwise needed generation additions.

Ranges of monetary values for individual dynamic operating and other benefits are shown in Table 4.

ENERGY STORAGE USES IN THE COMING UTILITY ENVIRONMENT

Rapid changes in the electric utility industry will significantly change the way energy storage is evaluated and used. As illustrated in Figure 1, the utility

Table 4 Range of dynamic operating benefits monetary value

Type of benefit	\$/kW[a]	\$/kW/yr[b]	\$/kW[c]	\$/kW/yr[d]
Generation (energy)			20–70	13–139
Generation (dynamic)		27		10–78
Generation capacity		\$500/kW	375–425	
Spinning reserve	0–150	68	100–200	
Thermal unit minimum loading	0–50			
Frequency regulation	0–150		20–150	
Black start	0–20		Variable	
T&D benefits			200–600	6–24
Transmission deferral		\$1M/mile		19–34
Customer benefits				14–150
Demand side management		144		0–200
Absorbing power purchases	10–50			
Planning flexibility/modularity	50–200			
Hedge against future uncertainty			200–400	
Air quality/environmental			100–200	

[a]Source: (27).
[b]Source: (28).
[c]Source: (2).
[d]Source: (29).

industry appears to be breaking apart from its traditional, vertically integrated form into separate businesses (30).

Two aspects of the coming electric industry restructuring may have a dramatic impact on utility energy storage investment decisions: 1. delamination or the breaking apart or the traditional generation, transmission, and distribution functions; 2. the weakening of monopoly market forces (31). Delamination will allow utility decision makers to concentrate on each portion of the business to make it as profitable as it can be, rather than optimizing large generation asset choices. This strategy will lead to more customer focus. Moving away from rate-of-return regulation (and toward performance-based ratemaking) will encourage utility executives to assess alternative capital investments more fully, and this change will create an incentive to consider new ways of doing business and the inclusion of emerging technologies (31–34).

Utility Business Trends and Their Potential Impact on the Use of Energy Storage

A trend has begun—in California (32), Wisconsin (33), and many other states—toward examining the very basis of the utility business: the regulated monopoly franchise. This business arrangement has given relative stability to the industry for over 100 years. Currently, a debate rages about the need for continued

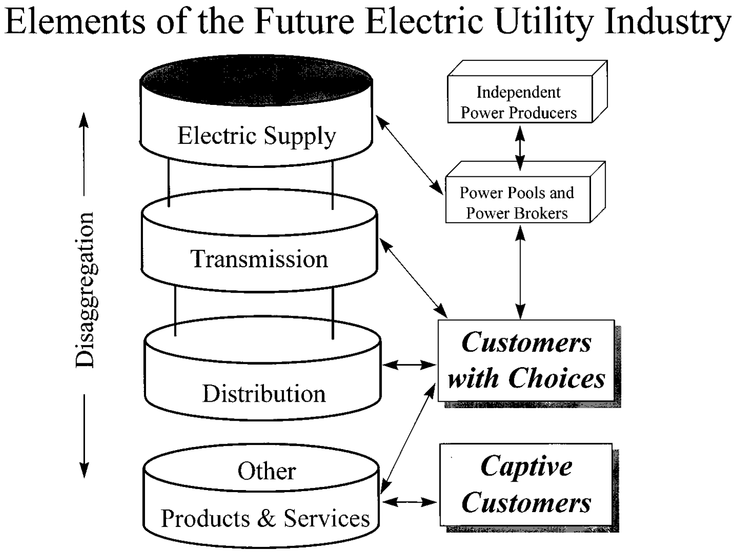

Figure 1 Utility industry restructuring.

monopoly operation. The national Public Utility Regulatory Act of 1986 (PURPA) and the Energy Policy Act of 1994 have legislated into existence a sizable independent power production capability. The emergence of unregulated competitors has been inconsistent from state to state owing to local definitions of avoided costs, environmental dispositions, and state tax policies. In most cases, Independent Power Producers (IPPs) have increased rate-payer energy costs. But their very existence and persistence in the midst of previous pure monopolies have caused regulators to question whether a free market could be established to encourage further competition and, in turn, benefit rate payers. Retail wheeling (an open market at the customer level) is the most extreme proposal being considered. Although municipal utilities, federal power agencies, and co-ops may not be directly impacted by these changes, the indirect impacts are far reaching and potentially just as important (31, 34).

In the spirit of preparing to support the storage technology needs of the utility of tomorrow, we examine how these trends could impact the way utilities invest in storage.

LOSS OF MONOPOLY OR UTILITY RETURN ON INVESTMENT These trends would lead to higher required discount rates and more cautious investment, a need for immediate utility shareholder benefits of all investments, more scrutiny of T&D

investments, and less concern with regulatory prudence oversight. Noncapital or low-capital solutions to utility problems will be more highly valued (e.g. pricing policies, rebates, etc). Companies with stranded assets will be hesitant to make further capital commitments, especially until the new rules are clear (31). Possible storage implications of these trends are as follows: 1. fewer capital investments of any type, including storage; 2. distributed storage use to help T&D asset utilization; 3. diversification into customer storage services. Although all three outcomes are possibilities, the occurrence of one would preclude the other two in any given scenario.

CONCERN ABOUT CUSTOMER BYPASS VIA RETAIL WHEELING Such a trend leads to a need to keep rates very competitive to avoid customer and market share losses. The customer becomes the decision maker, energy suppliers partner with major customers, and customer services are unbundled. The trend also leads to net metering for environmentally preferred technologies, improved and expanded customer services to discourage customer erosion, and an asset utilization improvement focus. Possible storage implications of this trend are as follows: 1. fewer capital investments of any type, including storage; 2. customer sited storage to provide better service, reliability, and/or power quality; 3. distributed storage use to help T&D asset utilization. The occurrence of any one of these outcomes precludes the other two.

LESS UTILITY CONTROL OVER SUPPLY ASSETS (OPERATION AND/OR OWNERSHIP) This trend leads to reliance on other companies (e.g. other utilities and IPPs) to ensure sufficient future energy supplies, increased transmission access, and extensive wheeling charges; short-term or spot market energy arrangements with some energy suppliers; long-term contracts with some energy suppliers; less transmission system stability, operating margin, and reliability; and wide variations in time-of-day costs to the utility. Possible storage implications of this trend are as follows: 1. distributed storage use to provide T&D stability and reliability; 2. large storage installations by utilities or regional power brokers to balance supply and demand, stabilize the transmission grid, increase revenue by buying low and selling high and improve transmission access; 3. customer-owned storage installations to circumvent some of the new utility problems (e.g. fluctuating time-of-use rates, high demand charges, poor power quality or reliability).

The trend toward utility business restructuring and cost disaggregation is thus expected to drive increased use of energy storage in dispersed locations. By artful placement of energy storage within the T&D infrastructure and at customer sites, utilities can minimize costs and maximize overall local service value and quality (21, 31).

Emerging Applications and Future Economic Benefits

Most traditional benefits of energy storage described previously will continue to exist during utility industry restructuring. However, the magnitude of those benefits and the way in which they are valued monetarily and shared among stakeholders will change, perhaps dramatically. In addition to the traditional benefits of energy storage, others will emerge. New benefits of energy storage will exist mostly because (*a*) Emphasis on optimizing economic value at the local level within the power distribution infrastructure will increase. (*b*) Utilities and energy services providers will provide value-added, differentiated, customer-specific services. (*c*) The value of planning and operational flexibility will increase as risk and uncertainty increase in the restructured electricity marketplace. For localized benefits to become significant, utilities will probably have to establish electric service pricing mechanisms that allocate utility costs among customers more precisely than existing electric tariffs.

BULK STORAGE BROKERING Bulk storage brokers are envisioned as a key element of a deregulated electricity marketplace. Hedging is the primary application for storage; it is physical insurance to enable energy availability so as to meet contractual power or energy commitments. Hedging also allows greater risk tolerance during negotiations about power prices. Storage technology, such as CAES and pumped hydro (especially with the addition of adjustable speed drives), is available to meet this need. Other technology options can also meet this need, albeit for smaller storage sizes. The key to extensive use of storage for hedging is cost and flexibility. The competition may well come from financial instruments for hedging rather than from other technologies.

UTILITY LOAD MANAGEMENT Load management is an ongoing concern of power generators and marketers for whom storage technologies may provide value. Some storage technologies are already available for ramping applications; however, the response rate may be inadequate. Both pumped hydro and CAES require faster-than-normal response rates to be useful in these applications. Flywheels and SMES have suitable response rates, but both need technical development, especially for large capacity. Batteries do not have adequate response for ramping applications but are ideal for peak shaving applications.

TRANSMISSION AND DISTRIBUTION T&D systems are a high-value (often underutilized) capital asset in utility systems. The T&D system segment affords a range of high-value storage applications (35). For transmission applications such as line stability and enhanced capacity, rapid response and four-quadrant control are required. All energy storage technologies can be designed to do these jobs, but none is currently mature enough, either in size or power interface. SMES is expected to have ideal characteristics, but it requires demonstration and operating experience.

Reliability, especially support for valuable loads located on radial distribution systems, is another substantial large-scale need in T&D systems that might be met with energy storage. In addition to cost criteria, environmental advantages for storage located at these positions may be key decision factors.

Response time, size, and cost are all important storage decision criteria for distribution applications. Flywheels, micro-SMES (toroidal or shielded), and possibly capacitors could be used for distribution applications. Battery systems are the closest to commercial readiness for distributed use.

Distribution Capacity Benefits As utilities begin to use distributed generation and storage, capacity benefits may also accrue to the distribution system. Energy storage deployed within the utility infrastructure may allow utilities to defer or avoid expensive upgrades of power distribution wires and transformers, if they are located at sites allowing them to reduce local capacity needs. Distributed capacity benefits can exceed $300/kW in locations with imminent distribution system upgrade requirements (36).

Distributed Dynamic Operating Benefits If distributed generation proliferates, local energy storage can provide dynamic operating benefits (described above for the central electric supply system) for the local generation network. Energy storage can provide local load–following to reduce (*a*) start-ups of local generation, (*b*) cycling of local generation, and (*c*) the total amount of local "peaking" generation capacity required. Storage may also provide distribution system operators with operating flexibility, allowing them to reduce the maximum load on distribution transformers, increasing transformers' useful life, and reducing O&M costs. This flexibility may also give operators alternative local means to increase local service reliability. Distributed energy storage can stabilize local power voltage, frequency, and power factor, thus increasing local power reliability and quality.

CUSTOMER SERVICE/POWER QUALITY High quality power and related specialized support services are an increasingly valuable element of supplying power to industrial and other large customers. Storage may have special use in applications such as momentary carryover for short outages to high-value industrial processes and/or plants, voltage support (e.g. for transit systems), and other aspects of power quality. These needs present utilities with an opportunity to provide new products and services. For example, premium reliability and power quality services described above could be provided, for a price, using on-site energy storage. Response time and relatively high power are the most desired storage system features, along with small footprint, low maintenance, good reliability, and of course, competitive cost. Micro-SMES, flywheels, and possibly capacitors are the likely storage technology choices for customer electrical power quality applications. Thermal and environmental control in large buildings also present an opportunity for thermal energy storage in the customer sector. The required systems are available but need further application experience and commercial maturity.

UTILITY ENERGY STORAGE DEVELOPMENT AND ANALYSIS NEEDS: CLOSING THE GAP

For energy storage to become common practice in the energy service sector, further advances in technology and in the methods for evaluating energy storage use are needed. The latter is actually more important because until users can model and evaluate the impact of storage, even the best technology will not be implemented. Although many of these efforts are clearly the responsibility of technology developers and users, federal leadership is also needed to foster the transition of energy storage technologies from the national laboratories in which they were developed to commercial practice.

Technology Development Needs

The energy storage technologies under development are already being designed to meet the needs of the utility of the future. However, demonstration (proof-of-principle) is needed for some, performance improvements are needed for some, cost reductions are needed for many, and system packaging is needed for most.

PROTOTYPE AND COMMERCIAL SYSTEM DEMONSTRATIONS Prototype demonstrations of SMES in sizes larger than micro-SMES, flywheels, and adjustable speed drives for pumped storage would be particularly useful. Extended demonstrations of batteries and SMES would be especially helpful for those trying to gain operating experience and establish commercial practices with these technologies. Small storage demonstrations on the distribution system would capture local benefits and operability. Costs for proposed prototype demonstrations range from several million to tens of millions of dollars.

ADVANCED DEVELOPMENT In a few areas, focused research or development could improve the performance or reduce the cost of energy storage systems to meet future needs. For example, both pumped hydro and CAES require faster response rates, i.e. faster turbine availability, to be useful in ramping applications. Also, CAES could be more widely implemented if less-expensive methods of cavity formation in hard rock were available. Another example is the development of shielded, or toroidal, SMES, which will make it available for on-site customer applications. These development efforts can cost nearly one hundred million dollars.

COST Development efforts to firmly establish costs for batteries, SMES flywheels, and advanced thermal energy storage systems would be helpful. Reduced component costs would be helpful for implementing all technologies. Research and development efforts to reduce power conditioning costs of power quality and system stabilization applications would be particularly useful because power conversion system costs dominate in these applications.

COMMERCIAL MATURITY Efforts are needed to produce low-maintenance turn-key storage systems, leading to commercial maturity. Such efforts are needed for all the modular technologies but especially for batteries, which are the closest to commercial packaging for distributed use.

Storage Benefits Analysis and Methods Needs

PROGRAMMATIC STORAGE MODELING AND ASSESSMENTS Significant gaps exist between current modeling and analysis tools and those needed to evaluate the many monetary benefits associated with energy storage use in the restructured electric power marketplace. Especially important is the need to understand how electricity purchase decisions will be made in the emerging utility marketplace and how to optimize the economic benefits from and penetration of energy storage. Top-down market assessments are needed, including background studies and the development of assumptions about energy and capacity demand and supply during and after restructuring. Bottom up analyses, including site-specific case studies, are also important because they provide much-needed validation of elusive and hypothetical distributed and dynamic operating benefits. They also comprise a statistical basis for larger market studies and help to define storage types, numbers of units, timing needs, and opportunities for energy storage in the emerging electricity market.

Quantitative data are needed on the many hypothetical or unproved benefits of energy storage, including the magnitude and range of each benefit and the degree to which benefits cancel each other out or overlap. These data would impact decisions about specific energy storage projects, utilities' willingness to accept energy storage in general, and researchers' and vendors' assessments of the market for new storage technology.

Cost analysis standardization is also needed. An especially helpful exercise would be to use a detailed storage cost structure breakdown (applicable to all storage technologies) to price out several standardized storage applications to create a direct cost comparison.

Market size, benefits, and cost issues are linked. Markets, by definition, have costs below the technology's value to the buyer. With a complete, credible, and accurate set of benefits and costs, the market can be correctly assessed.

EXISTING UTILITY STORAGE TOOLS AND NEAR-TERM APPLICATIONS OF THOSE TOOLS A second important development category is utility-grade tools and near-term applications of those tools, by or for the utilities. Current dispatch models that include storage [e.g. DYNASTORE (37) and DYNAMICS (38)] are built around utility business assumptions such as central station planning algorithms and rate-of-return regulations. The modern utility will also need to perform site-specific storage application analyses and high-level market or impact studies. Within this category, benefits assessments are most needed for utility-wide and distributed-storage installation benefits. Storage break-even studies (cost vs benefits) for specific utilities are key.

DEVELOPMENT OF NEW AND IMPROVED TOOLS TO EVALUATE STORAGE New types of models to study storage are also needed if storage use is to penetrate the utility of the future. Among these models are planning methods that include uncertainty analysis, models to automate electric circuit analysis, and new distributed storage application models that can fully trade central economies of scale with local benefits of storage, such as enhanced reliability or power quality.

CONCLUSIONS

Restructuring and deregulation in the electric utility industry, coupled with commercial availability of new technologies that convert, deliver, and store energy, provide a tremendous opportunity to increase the role of energy storage. As utilities separate into distinct business units, unbundle their services, and enter into new businesses, and as competitors enter the utility business, price pressures and competition are expected to create many new opportunities for cost-effective use of energy storage. Opportunities will be available soonest in bulk power brokering, utility load management, transmission enhancement, distributed or dispersed applications, and power quality service.

The greatest benefits are expected to arise in a restructured industry from technologies that are flexible, can deliver a burst of high power (>1 MW) on short demand, and can be sited near the point of application, either on the T&D system or near the load center or customer location. High reliability, low maintenance, and competitive cost are other essential features.

Although technology development and market analysis are still needed, technology demonstration, which provides operating experience and helps establish standardized commercial practice, is critical to utility industry acceptance of energy storage. The investigation of smaller storage technologies in market evaluation and site-specific studies is vital. Developers want to know if (and at what price) these technologies will sell to the utility industry, customers, or the other emerging participants in the electric business.

Because of the enormous opportunity to influence energy conservation and environmental benefits, federal assistance in moving energy storage technologies from the national laboratories to commercial maturity is welcome.

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