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Long- vs. Short-Term Energy Storage Technologies Analysis

A Life-Cycle Cost Study

A Study for the DOE Energy Storage Systems Program

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Abstract

This report extends an earlier characterization of long-duration and short-duration energy storage technologies to include life-cycle cost analysis. Energy storage technologies were examined for three application categories–bulk energy storage, distributed generation, and power quality–with significant variations in discharge time and storage capacity. More than 20 different technologies were considered and figures of merit were investigated including capital cost, operation and maintenance, efficiency, parasitic losses, and replacement costs. Results are presented in terms of levelized annual cost, $/kW-yr. The cost of delivered energy, cents/kWh, is also presented for some cases. The major study variable was the duration of storage available for discharge.

Acknowledgment

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Acronyms and Abbreviations

AC	alternating current
BESS	battery energy storage system
BoP	balance of plant
BTU	British thermal unit
CAES	compressed air energy storage
DC	direct current
DG	distributed generation
DOE	Department Of Energy
ESS	Energy Storage Systems
FERC	Federal Energy Regulatory Commission
HVAC	heating, ventilating, and air conditioning
LAC	levelized annual cost
Li-ion	lithium-ion
Na/S	sodium/sulfur
Ni/Cd	nickel/cadmium
O&M	operation and maintenance
PCS	power conversion system
PEM	proton exchange membrane
PJM	Pennsylvania, New Jersey, Maryland
PQ	power quality
PREPA	Puerto Rico Electric Power Authority
RR	revenue requirement
SMES	superconducting magnetic energy storage
TVA	Tennessee Valley Authority
UPS	uninterruptible power supply
VAr	volt amp reactive
V-redox	vanadium-redox
VRLA	valve-regulated lead-acid
Zn/Br	zinc/bromine

Executive Summary

This study is a follow-on to one documented in Sandia Report, "Characteristics and Technologies for Long- vs. Short-term Energy Storage," (SAND2001-0765). In that previous study, energy storage technologies were compared on the basis of power and storage capacity ratings, time response, and capital costs. A specific objective was to distinguish energy storage technologies on the basis of discharge time: long vs. short.

In this study, the energy storage technology costs have been updated and a life-cycle cost analysis has been performed to give a more complete representation of the comparison between technologies. Life-cycle costing provides the opportunity to include in the comparison differences in operating parameters such as efficiency, operation and maintenance (O&M) costs, parasitic energy requirements, and cycle or shelf life. The latter can also be viewed in terms of replacement frequency and cost. Results are presented in terms of levelized annual cost ($/kW-yr) and revenue requirements (cents/kWh).

The storage technologies included in this study are batteries (lead-acid and advanced, including flow batteries), flywheels (high-speed and low-speed), superconducting magnetic energy storage (SMES), supercapacitors, compressed air energy storage (CAES), pumped hydro and hydrogen. Technologies appropriate for three application categories were compared:

- bulk energy storage for utility load-leveling,
- distributed generation (DG) for local peak-shaving, and
- power quality or end-user reliability.

Some conclusions from this study are:

- Batteries (of one type or another) can address all application areas, although they are not always the least expensive option.
- Replacement costs influence significantly the life-cycle costs of batteries, much more so than other technologies. This factor also shows a distinct difference between battery types.
- CAES is very cost-effective for bulk energy storage and has potential for DG with the development of modular storage vessels.
- Flywheels are becoming available in a variety of types and with a range of capabilities, including some potential for DG.
- Power from systems consisting of hydrogen fuel cells and electrolyzers can only become attractive for DG applications with relatively long discharge times and with a reduction in capital costs.
- The life-cycle costs of power quality systems are dominated by capital and replacement costs. Other operating costs are minimal.
- For power quality applications, the best technology choice is strongly dependent on the discharge time required. For a one- to two- second discharge, SMES and supercapacitors are attractive, whereas at 20 to 30 seconds, some flywheels or battery systems are less expensive.

1 Introduction

1.1 Background

The United States Department of Energy (DOE), through the Energy Storage Systems (ESS) Program implemented at Sandia National Laboratories, is working with the electric utility industry and the manufacturing sector to develop energy storage systems for applications of value to the nation. Among these are specific applications for energy storage with varying requirements for power level and storage capacity. Numerous types of storage systems are available or are becoming available to meet these needs. It is important to identify suitable matches between requirements and the performance of various types of technologies. The overall goal of this project is to elucidate possible matches by examining both performance characteristics and costs.

The previous study, "Characteristics and Technologies for Long- vs. Short-term Energy Storage" (Sandia Report SAND2001-0765) [1], compared energy storage technologies with different discharge duration capabilities on the basis of power level, storage capacity, time response, and capital cost. The emphasis was on comparing technologies designed to have different discharge time capabilities, i.e., long- vs. short-term storage. In this follow-on study, technologies are also compared on the basis of life-cycle costs to give a richer picture of the differences between technologies.

1.2 Objectives

The objectives of this study were to:

- update technology data,
- compute life-cycle costs, and
- compare technologies for various applications on the basis of life-cycle costs.

In addition, a tutorial on the similarities and differences between rechargeable batteries and fuel cells for DG applications was included in the scope of work. This comparison is included in the Appendix.

This study extends the work of the previous study, which emphasized capital costs, by including in the comparison the effects of efficiency differences, O&M costs, parasitic losses, and replacement requirements that arise from different cycle or shelf lives. These operational differences can paint a different picture of the expenses associated with various systems than just comparing capital costs alone.

The technology status narrative in section 2 is provided because some technologies have evolved since the original study. Some capabilities and costs have changed (or become more certain) as well. Some new systems have become available and others are no longer in development or production. Flywheels and emerging battery types represent the technologies with the greatest development activities.

1.3 Applications

For this study, the applications of interest have been classified as bulk energy storage, for the purpose of load-leveling or load management, distributed generation (DG) for peak shaving, and power quality (PQ) or end-use reliability. These correspond to the categories of the previous study and also approximately to the categories of the recently published Phase II Opportunities Analysis. [2] The different categories are distinguished by the power level and discharge time required. These specifications together determine the stored energy requirement. The power levels and storage times for the various application categories are listed in Table 1.

Table 1. Application Category Specifications

Application Category	Discharge Power Range	Discharge Time Range	Stored Energy Range	Representative Applications
Bulk Energy Storage	10-1000 MW	1-8 hrs	10-8000 MWh	Load leveling, spinning reserve
Distributed Generation	100-2000 kW	0.5-4 hrs	50-8000 kWh	Peak shaving, transmission deferral
Power Quality	0.1-2 MW	1-30 sec	0.1-60 MJ (0.028-16.67 kWh)	End-use power quality and reliability

1.4 Scope

The technology types considered in this study are the following:

- Lead-acid batteries (flooded and valve-regulated lead-acid, VRLA)
- High temperature sodium/sulfur (Na/S) batteries
- Sodium bromide/sodium polysulfide flow batteries (represented by the Regenesys® system)
- Zinc/bromine (Zn/Br) batteries
- Vanadium-redox (V-redox) batteries
- Lithium-ion batteries (Li-ion)
- Nickel/cadmium (Ni/Cd) batteries
- Superconducting magnetic energy storage (SMES)
- Low speed flywheels (steel wheel)
- High speed flywheels (composite wheel)
- Supercapacitors
- Compressed air energy storage (CAES) in underground caverns
- Compressed air energy storage in surface vessels (CAES-surface)
- Pumped hydroelectric storage
- Hydrogen storage used with either a hydrogen fuel cell or hydrogen engine

Not all technologies are suitable for all applications, primarily due to limitations in either power output or storage capacity. Table 2 below lists the technologies considered for each of the application categories. The third column indicates whether the technology is currently available (A) for this application, or has the potential (P) to be used in this application.

Table 2. Technologies Considered in each Application Category

Category	Technologies	Available or Potential
Bulk Energy Storage	Lead-acid batteries	A
	Na/S batteries	P
	Regenesys	A
	Zn/Br batteries	A
	Ni/Cd	A
	CAES	A
	Pumped hydro	A
Distributed Generation	Lead-acid batteries	A
	Na/S batteries	A
	Ni/Cd	A
	Li-ion batteries	A
	Zn/Br batteries	A
	V-redox batteries	A
	High-speed flywheels	P
	CAES-surface	P
	Hydrogen fuel cell	A
	Hydrogen engine	A
Power Quality	Lead-acid batteries	A
	Li-ion batteries	P
	High-speed flywheels	A
	Low-speed flywheels	A
	SMES	A
	Supercapacitors	A

Some technologies that were included in the first study were dropped for this follow-on analysis because they were determined to be unavailable, at least in the near-term. One of these is SMES in sizes larger than the current micro-SMES or D-SMES products. While designs exist for large systems, and several much larger magnets are being used in laboratory studies, no products or integrated systems are currently being commercially developed. Another system that is not considered in this study is the fast-response hydrogen fuel cell. Several prototypes have been delivered for lab characterization, but commercial development is not active as of the time of this study.

1.5 System Descriptions

For the three application categories, a system configuration was assumed so that system costs and performance could be estimated. The bulk storage and distributed generation systems are shown schematically in Figure 1. The dc storage unit is assumed to interface to the ac electric grid through the power conversion system (PCS) that operates only when dispatched as source or load. The PCS is rated at the power level (kW, MW) required for the application and the energy storage unit is rated (kWh, MWh, MJ) to provide power for the required duration. For some technologies, the energy storage unit may be oversized if it cannot be completely discharged in a short period of time.

In a power quality or end-use application, the energy storage system may be connected to the bus that feeds a user's load such as a machine or industrial processing unit. In this case, the storage unit is only activated when the grid power is disrupted, but it must be in communication with the bus at all times so that operation is nearly instantaneous whenever a disturbance occurs on the system. This configuration is shown schematically in Figure 2. It can be implemented in several ways. In one implementation, the PCS is continuously energized and the energy storage unit may be trickle charged, resulting in energy losses due to PCS inefficiencies and storage unit charging. In another implementation of this configuration, the system may include a fast, high power switch that can connect the PCS and storage unit to the bus in about four milliseconds, which is a seamless connection for almost all loads. This implementation incurs fewer energy losses during normal operation, but requires the installation and maintenance of the fast switch.

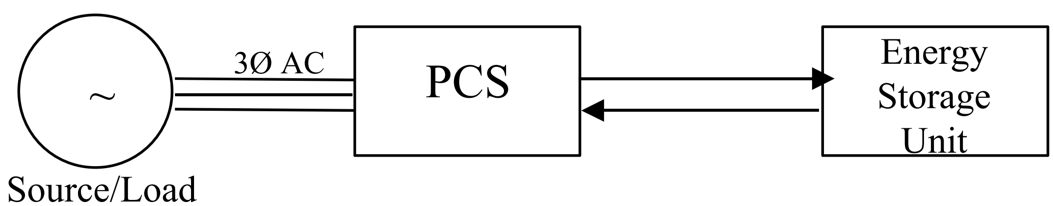

Figure 1. An Energy Storage System Connected Directly to the Electric Grid via a Power Conversion System.

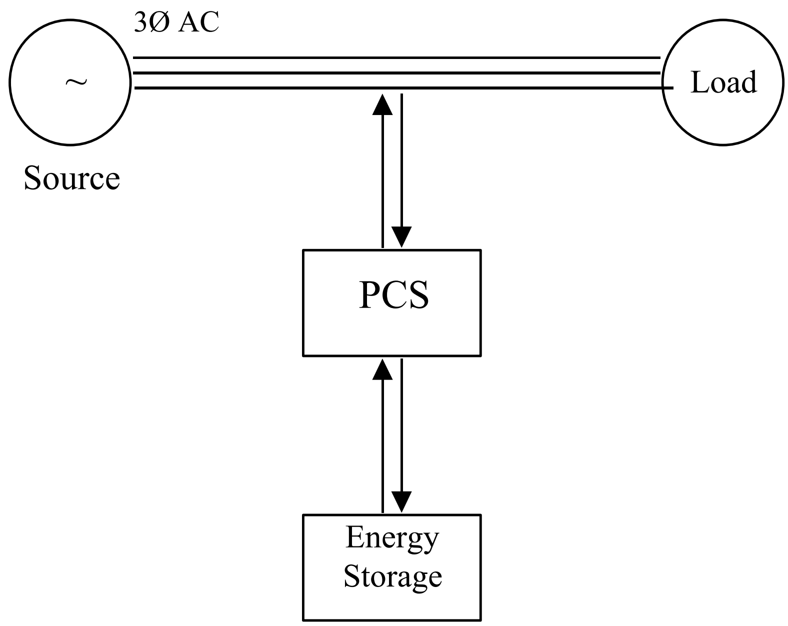

Figure 2. An Energy Storage System Connected to a Bus that Feeds the Load.

When using hydrogen as a storage medium, the system becomes somewhat more complicated, as indicated in Figure 3. In this case, separate charging and discharging interfaces are used. An electrolyzer (which incorporates a rectifier) provides the hydrogen during off-peak load times, while a fuel cell (which incorporates a PCS) or an engine, generates AC electricity from hydrogen. Although it is possible to use a reversible fuel cell to do both jobs, it is more cost effective to have separate subsystems because they are sized separately.

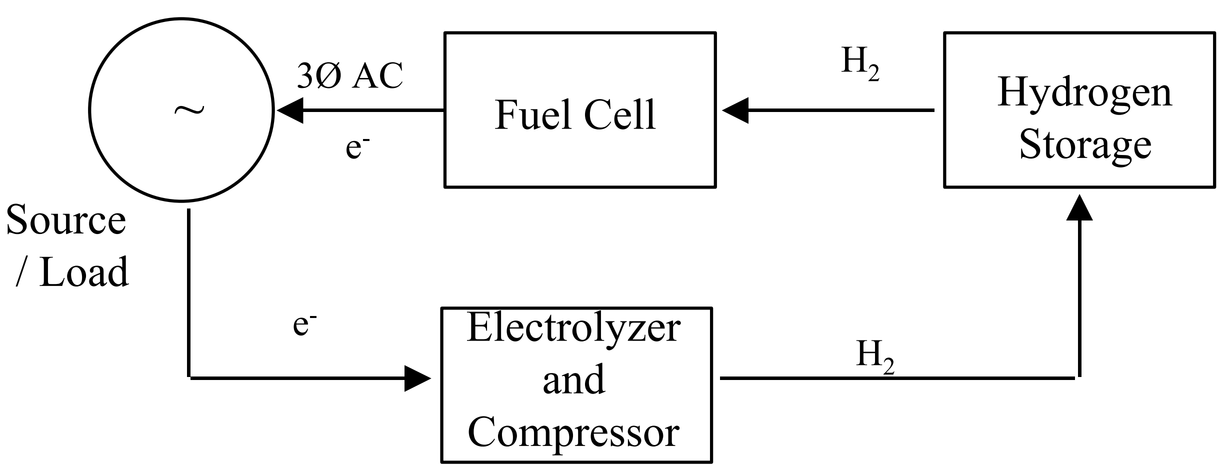

Figure 3. Hydrogen Energy Storage System Showing the Electrolyzer used to Produce Stored Hydrogen.

2 Energy Storage Technology Status

For the purpose of this study, energy storage technologies have been separated as discussed above into three categories: 1) utility scale or bulk energy storage, 2) distributed generation, and 3) power quality. Bulk energy storage includes those applications that are capable of delivering 10 MW or more for periods of one to eight hours, or more. Storage for distributed generation includes those technologies that can deliver between 100 kW and 2 MW for periods of 0.5 to 4 hours. Energy storage technologies that are appropriate for power quality applications can also deliver power levels up to 2 MW, but are designed for very short delivery periods: a few 60-Hz cycles to about one minute. These categories are, at some level, rather arbitrary divisions. They do however provide a good separation for the analysis of the various technologies and allow estimates of life-cycle costs and comparisons.

This section of the report describes each of the various technologies in each of the three different energy storage categories. These technology descriptions include information on system design, system performance, existing and/or projected costs, and technical maturity. The major purpose of these descriptions is to develop the technology costs that will be used later for the life-cycle cost estimates, which are summarized in tables at the end of this section. Technical descriptions are included to the extent necessary to provide definition of the technology under consideration and to support the cost estimates. Thus, their depth and extent are limited and vary from technology to technology. When a technology can be used for more than one of these categories, the technology is described once, and in subsequent sections the technology differences, principally costs, are described.

Many of the technologies use silicon-based electronic equipment that functions as the interface between the storage device and the electric power system. They convert between AC and DC or variable frequency AC. A brief description of a generic power conversion system with anticipated costs for the various technologies and power ratings is given at the end of this section.

Several caveats are appropriate before discussing the individual technologies in each of the three categories.

- As manufacturers have searched for ways to increase the value of their storage technologies, they have developed single installations that can address more than one application. For example, an installation may supply power at one capacity for hours for peak shaving or load leveling and provide power at a much higher level for several seconds to meet power-quality demands. This trend is seen as one that will increase if deregulation assigns specific value to ancillary services as defined by the Federal Energy Regulatory Commission (FERC) document 888. This analysis, however, does not explore multiple revenue streams for the technologies. An analysis of multiple revenue streams would include adding revenues from each source while ensuring the applications were not mutually exclusive. A complex energy dispatch algorithm is necessary for each combination of applications, which is beyond the scope of this study.
- The installed price and the cost of maintenance are given for each of the technologies in a way that can be used to estimate life-cycle costs. In many cases,

however, the technologies are still being developed, and costs are based on manufacturers' projections assuming a "mature" production volume for the technology, e.g., tens or hundreds of units per year.

- In almost all applications, particularly for large scale systems, the installations are composed of multiple units or cells that are combined in series and/or parallel arrangements to achieve the system rating for power and stored energy. For example, battery systems almost always have cells in series to form a string with an appropriate operating voltage and multiple strings in parallel to achieve the total stored energy. Similarly, pumped hydro systems have multiple turbines, each of which operates most effectively at a specific power output level. Total system cost is based on anticipated use of multiple units.
- Obtaining detailed technical information and costs for some of the technologies, particularly those under development, proved to be difficult. As a result, some of the cost figures used here may change as the technologies reach full development or as competition with other technologies drives prices down.

It should be noted that although most of the data values presented in this section were derived from discussions with vendors or from published literature, most are presented without references to maintain the confidentiality of the sources.

2.1 Bulk Energy Storage Systems

2.1.1 Lead-Acid Batteries: Flooded for Bulk Storage

Lead-acid batteries have been used for energy storage for over a century and are used today in several large installations. The estimated energy storage cost of the batteries is about $150/kWh, which has changed little since the mid-1990s. Large battery plants have extensive costs associated with the balance of plant (BoP). For example, the BoP costs for the Southern California Edison plant at Chino and for the Puerto Rico Electric Power Authority (PREPA) battery energy storage system (BESS) were about the same as the cost of the batteries themselves. These costs include building construction, battery installation, interconnections, heating, ventilating, and air conditioning (HVAC) equipment, etc. The cost of the power conversion system has decreased somewhat since the time of these installations as variable-speed motor technology has improved. Today, a 20-MW PCS rated for continuous use for a battery based storage system is expected to cost about $125/kW, assuming the 10th identical unit, as discussed in the PCS section below. In addition, PCS capability has changed somewhat so that the functionality of the system has improved. Nonetheless, most lead-acid batteries must be replaced every five or six years, based on manufacturers' projected battery performance data for deep discharge applications. (For some other battery types, battery life is considerably longer.)

Efficiency of a lead-acid battery energy storage system for an AC-AC cycle is about 0.75. It can be as low as 0.70 and as high as 0.8 under some conditions. Typically, for daily cycling, the latter value can be achieved and is used for this study. If the batteries are replaced every six years, there is little need for variable O&M for a plant. However, some scheduled maintenance is required. Water must be replaced in the cells every few weeks; temperatures must be measured on a continuous basis at multiple locations in a large facility, etc. The O&M estimate used here assumes that a single person, eight hours per day, 365 days per year, is required for maintenance for a plant of 20 MW. This translates into approximately $15/kW-yr.

2.1.2 Lead-Acid Batteries: Valve-Regulated for Bulk Storage

In many respects, Valve-Regulated Lead-Acid (VRLA) batteries are quite similar to conventional lead-acid batteries. They have about the same efficiency (0.75 is used here), are somewhat more expensive—$200/kWh, and need to be replaced more often in some applications, i.e., every five years. The PCS for a VRLA based energy storage system will be the same as for a conventional lead-acid system. The most significant difference is the fact that they have been claimed by some to be maintenance-free, which is true to some extent, but is a misnomer in another sense. There are no truly maintenance-free battery systems. On the other hand, the maintenance frequency for VRLA installations is considerably less than for those with conventional lead-acid batteries. The fixed annual O&M was reduced to $5/kW-yr to reflect this difference. Note that the reduced need for maintenance can be important for small systems where the avoidance of monthly or bimonthly service has an impact on life-cycle cost.

2.1.3 Nickel/Cadmium for Bulk Storage

A single Nickel/Cadmium battery storage facility under construction today almost meets the minimum size capabilities for bulk energy storage. The facility is under construction in Alaska. Batteries will be installed and the plant is scheduled to become operational in 2003. The following are estimates of the costs of various components based on a limited set of data for the overall installation. The total cost is $30M for a 13-MWh (1/2 hour, 26-MW) plant near Fairbanks, Alaska. The plant is actually rated at 6.5 MWh and 26 MW (15 minutes) for initial operation. The installed converter has a capacity of 40-MW continuous. This data is used to extrapolate the following. Using the per unit converter costs from a lead-acid battery plant, the total converter cost is $10M. The cost of installing external non-storage related facilities such as transmission lines, etc., is uncertain, but is estimated to be $6M. The balance of plant should be the same as for conventional lead-acid batteries, or about $3M, based on an eventual capacity of 20 MWh. This leaves about $12M for the initial set of batteries. This gives a cost of $900/kWh. This cost seems to be high, and the battery manufacturer projected costs of about $600/kWh. The life of these batteries based on one deep cycle per day is about ten years. Maintenance for Ni/Cd batteries is expected to be about the same as for VRLA batteries, i.e., $5/kW-yr.

2.1.4 Regenesys® for Bulk Storage

Several types of flow batteries are under development today. The only one that is at the level of large-scale demonstrations today is called Regenesys®. The technology is referred to as a flow battery or as a regenerative fuel cell. It uses sodium bromide as the active material in the positive electrolyte and sodium polysulfide in the negative electrolyte. During discharge, the electrolytes flow through a half-cell on opposite sides of a polymer membrane, producing about 1.5 V. High-voltage is achieved by stacking cells electrically in series in bipolar modules. These cells are connected in parallel hydraulically and are fed by a pump and distribution system running to the electrolyte storage tanks. The power-generating component is based on 100-kW modules that consist of 200 of the 1.5-V cells.

Two Regenesys® plants are under construction at present. One is at Little Barford in England and the other is on the Tennessee Valley Authority (TVA) system in Mississippi. Both plants have ratings of 120 MWh of energy storage and about 15 MW of power capacity. Various values for their costs have been presented, but the cost of each is probably between 35 and 40 million dollars. There is, however, a clear indication that these two plants are pilots or demos and that their costs are not representative of those of future plants which will probably have greater capacities. The manufacturer estimates that the cost for an nth-of-a-kind plant of the Little Barford design would be about $19M, which can be separated into three components. The power conversion cost is that of the converter plus the stack modules that contain the cells with separators etc., and the pumps that circulate the reactants. These costs amount to about $300/kW. The combined energy storage cost and balance of plant cost is then about $150/kWh. For lack of a better solution, these are split into $100/kWh (a number quoted for the storage cost in some earlier estimates) for the energy storage portion, and $50/kWh for the balance of plant. The efficiency of the plant is between 0.65 and 0.7. The lower value is used in this study.

Replacement costs for a Regenesys® flow battery are a combination of several components. The membranes used in the cells and the pumps that circulate the electrolytes are operated in a very conservative way and are expected to last about ten years. The stack replacement cost is estimated at $150/kW. Some of the electrolyte materials are consumed in the process of normal operation and must be replaced. The cost of replacement can be applied as a variable O&M or as a fixed annual replacement cost. Two numbers have been estimated for this component. One is $0.01/kWh for every kWh of energy delivered, and another is $10/kWh of capacity per year. The latter value is used here, though it may prove to be less in the future.

2.1.5 High Temperature Sodium/Sulfur for Bulk Storage

A Japanese company, NGK Insulators (referred to here as NGK), is manufacturing sodium/sulfur batteries for stationary energy storage applications. The advantages of these batteries over previous Na/S systems are their larger cell size and longer life, both of which reduce life-cycle costs. The AC-AC efficiency of large modules of these cells in operation is about 0.70, based on operation in a diurnal storage mode. Several technical issues that plagued earlier systems seemed to have been solved and several complete systems are installed and operating. There are several opinions as to the expected long-term cost of such a system. NGK projects that, in the long run, a cost of less than $250/kWh will be possible for their batteries. However, based on production levels anticipated in the near term, the price will be at least twice that value, about $600/kWh. In each case, the figures include packaging, installation, and balance of plant. The values used for this study are $250/kWh for the energy-related portion plus $50/kWh for the balance of plant. Anticipated cost of power conversion equipment is $150/kW, which is slightly larger than for other batteries. It is worth noting that no added heat is required to keep them functional if they operate on a diurnal cycle. Rather, heat may need to be rejected from the system under diurnal operation.

The expected life of a large-scale, high-temperature Na/S plant is uncertain at present. However, two things are clear: 1) cell life has improved considerably with recent cell developments, and 2) cell life is related to both the depth of discharge and the rate of discharge. The working number for the life of cells available today, based on accelerated life tests, is about ten years for 250 cycles per year. NGK is attempting to include larger capacity PCS components on some of the facilities. It is not clear exactly how this will impact cell life and it is beyond the scope of this study to evaluate the impact of adding a PQ function to an existing system. Though operating data are available for the developmental systems, operating costs of very large Na/S, systems are relatively uncertain. Slightly higher levels of maintenance are projected here than those required for lead-acid batteries, i.e., $20/kW-yr.

2.1.6 Compressed Air Energy Storage (CAES) for Bulk Storage

Compressed air energy storage (CAES) facilities have three major components: 1) a compressor, that is driven by a motor during off-peak periods; 2) an underground storage medium, such as a salt dome, an empty mine, or an aquifer; and 3) a combustion turbine that drives a generator during high-power demand periods. Two CAES plants are in operation today. One plant is in Huntorf, Germany, and was constructed in the late 1970s, and the other is in McIntosh, Alabama, and was constructed in the early 1990s. Both systems use solution-mined, salt caverns as the gas storage reservoir. They are available for peak power delivery over 90% of the time, and are reliable, regularly dispatched components of their respective power systems.

The heart of the CAES plant is a gas turbine that operates at a high temperature, and because of this is one of the most efficient engines for converting heat into electrical power. There is considerable development today on turbines for a variety of applications. Conventional turbine efficiencies may exceed 0.40. A conventional gas turbine generator consists of a turbine that is driven by expanding gases, and a compressor, which compresses the gas prior to combustion. The compressor consumes about 60% of the mechanical energy that is delivered to the shaft of the turbine. The remaining 40% is available to drive an electric generator and/or other equipment. Thus, for example, a 50-MW combustion turbine that drives a 30-MW compressor would produce 20-MW net electrical power. In a CAES plant, such a turbine would be connected to a 50-MW generator and would be physically separated from the compressor. Thus, the turbine delivers two and a half times more power to the grid than it would have under conventional operation in which significant power is diverted to the compressor.

CAES plant costs have two components that are easily separable. The first is that of the storage media, which, in locations where it is available, is generally very inexpensive—whether it is salt domes, hard rock (mines or other caverns) or porous rock (aquifers or old gas/oil areas). The energy-related costs are approximately $3/kWh, based on historical experience. The power-related costs are based on the cost of conventional gas combustion turbines, and ancillary equipment for generation, gas compression, etc. The power-related costs for modern equipment are approximately $425/kW. The power trains for the two existing installations are not representative of today's technology, which operates at a higher temperature and is therefore more efficient, in terms of converting British Thermal Units (BTUs) to kW. The appropriate performance values for a modern CAES plant in the 100+ MW range are 0.73 kW in for each kW out, and a heat rate of 3800 BTU/kWh at full power, ranging down to 1.1 kW in for each kW out and a heat rate of 4400 BTU/kWh at 25% power.

Other than these performance improvements, the same values for maintenance costs as were presented in the previous study were used, i.e., \$2.5/kW-yr for fixed O&M.

2.1.7 Pumped Hydro: Conventional for Bulk Storage

Pumped hydroelectric energy storage is an energy storage technology that is based on conventional hydroelectric technology. Units have been installed to store excess energy generated by coal-fired and nuclear power plants at night for later use during peak demand periods. The oldest pumped hydro plant in the US was constructed in Connecticut in 1928-1929 and consists of two, 3-MW reversible turbines. At present, the U.S. has 38 pumped hydro storage plants, with a total of 139 turbine motor generators and a total capacity of about 19,000 MW. The most recently completed U.S. pumped hydro plant is Rocky Mountain, near Atlanta, Georgia. It consists of three turbines each with a capacity of 282.5 MW. There are no new planned pumped hydro plants in the U.S., but there are several under construction in other countries, mainly China and South America.

Hydroelectric power requires a considerable volume of water to produce energy. The following equation describes the relationship between the volume of water (V, in cubic meters), the stored energy (E, in kWh), and the average head driving a turbine (h, in meters), and assumes 0.90 efficiency in energy conversion for electricity production.

$$V(m^3) \approx 400 \frac{E(kWh)}{h(m)} \qquad (1)$$

Using this relationship, a reservoir one kilometer in diameter, having an average head of 200 meters, and holding enough water for 10,000 MWh, would be filled to a depth of 25 meters. These are large installations and require considerable planning as well as environmental and other permits.

The efficiency and cost of a pumped hydro plant depend on a variety of factors including the head of water, the civil costs of excavation, tunneling, dam building, etc. An average value for the power-related part of installations under construction today is \$1000/kW, while the cost of the storage component is relatively inexpensive, at about \$10/kWh. The typical round-trip efficiency of large plants is about 0.75. This technology has been the primary type of energy storage for utilities to date. Today, however, only a few locations exist where adequate water and sites for upper and lower reservoirs are available.

For this economic analysis, transmission lines to and from sites are ignored. Annual maintenance is essentially fixed, as the system is assumed to operate close to full storage capacity more than fifty percent of the year. A 1000-MW plant requires three persons around the clock plus two more for other maintenance. Estimating 25 full-time people at loaded salaries of \$100K per year gives a total of \$2.5/kW-yr. The base efficiency used for pumped hydro was 0.75. Variable O&M is small.

2.1.8 Pumped Hydro with Variable Speed Turbines for Bulk Storage

A variation on the conventional pumped hydroelectric plant is based on the use of adjustable- or variable-speed turbines. No adjustable-speed pumped hydro plants exist in the U.S. This is because the last pumped hydro plant constructed in the U.S. was completed in 1995. At the time this plant was being designed, the variable-speed turbine and associated electrical and electronic equipment needed was still under development. The main effort to bring this technology to market has been in Japan. After several model plants were constructed and tested in Japan, a full-scale developmental installation was designed in the late 1980s and was completed in 1993. The 395-MW variable-speed turbine and associated motor generator were designed and built by Hitachi and installed in Kansai Electric's Ohkawachi No. 2 unit.

An adjustable-speed pumped hydro plant is based on a turbine and motor generator that will operate over a range of rotation speeds that is 10% above and below nominal. This speed variation is accomplished by using a solid rotor with a three-phase winding that can be driven at a variable frequency. A cycloconverter changes AC power to the appropriate frequency via an AC-DC-AC converter. The stator, as in a conventional pumped hydro plant, is directly connected to the three-phase bus and is energized at line frequency. The modest ±10% change in rotation frequency has a significant impact on performance. The 20% variation in rotational velocity translates into a 50% change in power output because mass flow is related to the third power of the rotational speed.

An adjustable-speed pumped hydro plant has several advantages:

- There is no need for a pony motor to start pumping.
- Synchronous power operation covers a wider range than for a conventional turbine, from below 70% to full power.
- The rate of changing the power output is driven by inertia of the water flow and is much more rapid than conventional pumped hydro.
- Full power output can be delivered from water-head variations of a factor of two.
- Rotational speed can be adjusted to avoid resonances within the equipment and cavitation modes in the water flow. This leads to longer life and less maintenance.
- Higher overall efficiency, as high as a 0.3 improvement on an annual basis is possible.
- Speed regulation provides frequency regulation to the grid.

However, improved performance comes with extra design and construction issues and costs.

- Motor/generator balance is more critical and takes multiple adjustments prior to initial operation.
- Higher speed rotation >350 rpm is required to obtain maximum performance.
- The motor/generator/turbine shaft is longer, which requires more excavation, increasing civil engineering costs.
- There is some additional cost for the cyclo-converter, but it is partially offset by the electronic conversion needed for starting conventional plants.

These factors increase the motor/generator/turbine cost by about 10% over that of a conventional turbine. As a result, the cost of the power component of the adjustable speed plant is $1,050/kW, which is slightly more than for the conventional plant. The cost for storage is the same, $10/kWh. The efficiency, however, is greater at about 0.78.

Several of these plants are now installed in Japan and others are in design or under construction. The general philosophy of recent pumped-hydro plants has been to install equal numbers of adjustable speed turbines and conventional turbines. This approach seems to provide adequate flexibility for operation over a wide range of pumping and generating scenarios.

2.2 Energy Storage for DG

In general, the information for distributed generation storage presented here is similar to that in the section for bulk energy storage. However, these systems are much smaller in size and are expected to be placed in an existing facility, which reduces the balance of plant cost.

2.2.1 Lead-acid Batteries (Flooded and VRLA) for DG

Lead-acid batteries have been used for energy storage in several large installations. The estimated energy storage cost of the batteries is about $150/kWh, installed in trailers, where balance of plant is estimated to be about $50/kWh. The average cost of the PCS for systems in the 0.5- to 2-MW range is expected to be about $175/kW for continuous rating—assuming the 10th identical unit. The batteries must be replaced every 6 years for flooded cells and every five years for VRLA. Efficiency of the system is about 0.75, and can be as high as 0.8 under some conditions. Maintenance costs for a 2-MW plant are based on a service contract of about $30K per year (or $15/kW) for flooded cells and $10K for VRLA batteries. Note that there are no systems meeting these exact conditions on the market today.

2.2.2 Nickel/Cadmium for DG

The costs for Ni/Cd batteries for DG are essentially the same as for bulk energy storage applications. The converter and balance of plant costs are the same as for lead-acid batteries above.

2.2.3 Zinc/Bromine Batteries for DG

The zinc/bromine (Zn/Br) battery for DG is a flow battery system where the electrodes, i.e., the power/voltage charging and discharging portion, are separate from the energy storage liquids and the circulation system. The battery works by plating zinc onto an electrode during charge and then removing zinc during discharge. This type of battery is optimal for long-term energy storage as it can be designed to achieve very low self-discharge when the system is in standby. For this application, the fluid electrolyte is drained from the cells and added to the fluid already in the storage tanks. Restart under these conditions requires activation of the circulation system, allowing the battery to deliver maximum power within 30 seconds. The system can also be operated as an uninterruptible power supply (UPS), delivering maximum power within a few 60 -Hz cycles. This capability requires operation of the circulation system approximately once per hour to maintain some active fluid in the cell stack which does increase the self-discharge rate. Today there are about 2.5 MWh of Zn/Br batteries installed in utility and manufacturing facilities.

The standard, container-enclosed units that are being built today have 250-kW capacity and can deliver 500 kWh with a round trip efficiency of about 0.65, AC to AC. These units consist of a single converter and ten modular, 50-kWh battery units. Today the installed cost of the battery portion (DC) of the unit is $400/kWh, thus a 500-kWh unit will cost $200K. The power conversion portion of the system costs an additional $250/kW. The latter cost will be higher for smaller units and will decrease for units of 1 MW or greater. This study uses the same converter cost of $175/kW as for other batteries. The expected life of the battery depends on the operational mode. It is expected to survive about 2000 cycles with limited degradation, which would be manifested by a decrease in efficiency to 0.60 or less. Expressed differently, the battery would exhibit a decrease in total stored energy from 500 kWh to about 450 kWh. This study uses an eight-year replacement cost for the Zn/Br battery, which is $100/kWh.

The estimate of O&M costs is based on the use of service contracts of $5K per year for 250-kW units, or $20/kW. The service cost is expected to decrease for larger installations, but is uncertain at present.

2.2.4 Lithium-Ion Batteries for DG

There are no large Li-ion battery installations at this time. They are primarily used for laptop computers and a variety of small applications. They are of interest, however, because they have power densities (kW/m^3), energy densities (J/m^3), specific powers (kW/kg) and specific energies (kW/kg) that are significantly greater than the batteries discussed above. The largest installation under construction in the U.S. today is a 100-kW, one-minute system. The cost of this unit is not representative of the eventual cost of a DG system. However, individual cell costs and known life times and efficiencies can be extrapolated to a storage plant. Interim numbers suggest that costs are about $500/kWh of installed storage with converter costs slightly higher than those for lead-acid batteries, which are around $175/kW because of charge equalization issues. A Li-ion system's lifetime should be on the order of 2000 cycles, or six to ten years. Since there is no long-range operational information, we use ten years. Efficiency (DC) is expected to be relatively high for this technology; we use 0.85 for the system efficiency.

2.2.5 Vanadium-Redox Batteries for DG

Vanadium-redox flow batteries are a relatively new energy storage technology. Several vanadium-redox systems have been installed in locations outside of the U.S. Systems have been demonstrated in sizes up to 1.5 MWh with power ratings up to 1.5 MW. Commercial costs are not generally available, but quotes were provided for the Boulder City feasibility study. [3] Whereas Boulder City was considering a system of a scale that would be considered "bulk" in this analysis, actual products are not available in such sizes. Here, vanadium-redox is considered only for DG applications. Based on the study's projections, the following costs have been used here: $175/kW for the PCS, $600/kWh for the battery system, $30/kWh for the BOP, a replacement cost of $600/kWh every ten years, and fixed O&M of $20/kW-yr.

2.2.6 Small, Surface Mounted Compressed Air Energy Storage for DG

Small compressed air energy storage systems (CAES-surface) have been proposed for DG applications. In this technology, the compressed air is stored at high pressure in steel pipes that are typically used for natural gas transmission. These pipes are relatively inexpensive and are generally available. They can be placed on the surface or buried at a modest depth for safety. Units between 50 kW and 50 MW are possible. System costs were developed in a pilot study by Bechtel in 1986 [4] and seem not to have changed significantly. Because there are no installed examples, however, the projected cost estimates are quite uncertain. The two major cost items are for the turbine/compressor/generator (power-related cost) and the steel storage pipes (storage-related cost). Smaller turbines and generators are more expensive than the larger units included in the bulk storage section, ranging upwards of $550/kW installed. The storage of energy in this manner is very similar to that of the storage of energy in a flywheel. The steel in the walls of the tank and that in a rotating wheel are both put into tension as energy is stored. In both cases, the function of the structural material is to contain the resulting force. It can be shown that the amount of structural material needed to store a given amount of energy is the same for the two technologies. As a result, the energy storage related cost (essentially the cost of the tank) should be about the same as that of the steel of a flywheel, or \$120/kWh. The cost of installation of the compressed air tanks and the balance of plant is about \$50/kWh. These small systems can be designed to have slightly higher efficiency than conventional CAES plants, so 0.79 is used. Maintenance costs however, are projected to be higher. A fixed O&M of \$10/kW-yr is used for this study.

2.2.7 High Speed Flywheels for DG

Over the years, there have been several proposals for the use of flywheels for energy storage applications. A variety of technical hurdles have limited their use in this area, however. Perhaps the most significant has been the need to reduce parasitic losses associated with windage and bearings. Today, at least two companies are developing flywheels for distributed generation energy storage. Both are aiming for wheels in the size range of 30 to 50 kWh with converters in the 10- to 20-kW range. Larger installations would require multiple units or farms. The projected energy related costs for a 50-kWh system is about \$1000/kWh, and the power related component is about \$300/kW, which consists of a motor generator and a converter. The individual units are being planned for operation with no annual maintenance, but with possible bearing or other system maintenance on a three- to five-year basis. Efficiency is very high for these wheels, estimated at about 0.95, but there is a parasitic loss, even on the best systems. Flywheels have a long life, with no significant replacements over 20 years expected.

It should be noted that there has been considerable debate over how to describe different types of flywheels. Some prefer "low speed" vs. "high speed," others "steel vs. fiber-composite." This study uses the former terminology. However, as the flywheel technology for utility-scale, energy storage applications moves from developmental to practical, a distinction based on parasitic losses and thus on bearing technology may prove to be a better descriptor.

2.2.8 Hydrogen Fuel Cells and Engines for DG

As discussed in section 1, hydrogen-based systems can only be considered as energy storage technologies if the production and storage of hydrogen is part of the overall system. If hydrogen is simply supplied as a consumable or produced from the conversion of natural gas, then such a system is a generator and is not really a storage system.

In this study, hydrogen-based systems with either a fuel cell or a combustion engine as the power unit were considered for DG applications. The hydrogen is generated by electrolysis of water and stored as pressurized gas in a tank, as shown previously in Figure 3. There are many fuel cell products on the market. Those suitable for the application described here would be proton exchange membrane (PEM) type fuel cells. These operate on hydrogen and air at ambient temperature with good time response and relatively high efficiency. Although cost projections have been presented for PEM fuel cells of \$500/kW and lower (less than \$50/kW for automotive fuel cells in mass production), these prices have yet to be achieved. A representative cost for a PEM fuel cell of \$1500/kW is used in this analysis. Hydrogen storage tanks are relatively inexpensive: \$15/kWh for storage is used. Electrolyzers are commercially available from a number of suppliers in various sizes and at output pressures up to 20 bar. A commercial price of $300/kW is used. The results are somewhat insensitive to the cost of the electrolyzer, in any case, because the system is designed to operate at low power level, refilling the storage tanks, during all hours of the day when the generator is not use.

An alternative to the fuel cell is to burn the hydrogen in a combustion engine. Diesel engines have been modified for this task and produce electricity at a relatively high efficiency for an engine 0.44. [5] The overall system operates the same as the fuel cell system. The advantage of the engine is the relatively inexpensive power generation, at $300/kW.

2.3 Power Quality Energy Storage Systems

2.3.1 Lead-Acid Batteries for Power Quality

Several battery and power system manufacturers supply lead-acid battery-based power quality systems. We use an example where good experience (over 60 MW in the field) and cost information are available. Individual modules are rated at 250 kW. Discharge is limited to short duration, up to 30 seconds. Longer discharge is possible under a variety of conditions. The batteries, however, store about 40 kWh at the 10-minute discharge rate. The battery module costs $12K for a 250-kW system, or $300/kWh. This module must be replaced every six years. Cost of the PCS is $410/kW at this size and will decrease to about $250/kW for larger sizes. There is no clear need for O&M, fixed or variable. However, a service contract that is the equivalent of fixed O&M, amounts to about $20K for a 2-MW system or $10/kW-yr. Parasitic loss is in the form of occasional trickle charge and is small.

2.3.2 Li-Ion Batteries for Power Quality

Li-ion batteries for power quality are assumed to have essentially the same characteristics and projected costs as those for DG. However, like most batteries, Li-ion batteries cannot be completely discharged in a few seconds. Like a PQ lead-acid battery, a 10-minute storage system is assumed. Another difference is in the way the converter losses are handled. Because the converter may be connected full time, there can be continuous converter losses.

2.3.3 Supercapacitors for Power Quality

In general, capacitor systems store energy as an electric charge on two materials that are separated by a dielectric. Conventional capacitor systems function by having metallic plates separated by thin layers (10s to 100s of microns thick) of a dielectric that is usually a polymer. A variety of techniques are used in these capacitor systems to obtain large areas. The super- and ultra-capacitor systems carry this approach to an extreme that is not possible with layers of metal and plastic. The approach is to use two layers (an anode and a cathode) with mats of carbon or metal filaments that are perfused with liquids that serve as the dielectric. The advantage of this design approach is that the effective areas can be ten thousand times those of conventional capacitor systems. The downside is that the voltage must be held below 1.5 to 3.0 V to avoid electrolyzing the liquid used as the dielectric.

These supercapacitors are ideal devices for power quality and short-term energy storage. For some capacitor systems, this is less than one second, whereas for others it can be as long as a few minutes. Individual units store a limited amount of energy, however depending on design, a great deal of it can be removed in a second or so. Today, because of limited production and inexperience, the costs are rather high. A typical price is $50 to $100 for an 8-kJ unit ($45,000/kWh). In mass production, the unit price should be about $25,000/kWh.

Because of their small size, many of these devices must be paralleled to achieve a functional system. The cost of interconnections, protection, and packaging add about 20% to the unit cost. As a result, we assume that the cost for a power quality system will be on the order of $30,000/kWh. However, such systems would not be purchased based on energy costs, but rather based on power cost. Power conversion systems will cost about $300/kW. The value is higher than some systems because the converter must operate over a wide voltage range. The efficiency of the capacitor systems at design discharge rates is on the order of 0.95 in all cases. This decreases when they are discharged more rapidly than their design rating.

2.3.4 Low Speed Flywheels for Power Quality

Data are available from several manufacturers of low-speed, mainly steel-based, flywheels. These systems are installed in many locations and have many different configurations. They often provide an interface between critical portions of a local load and the power grid and are frequently part of an installation that includes separate power generators, such as diesel engines. In the latter case, the flywheel provides ride-through power for a period of seconds while continuous power sources are brought on line. The data used came from several manufacturers of PQ flywheels to obtain a benchmark for system costs and extract various components to obtain both power and energy related costs.

The first piece of understanding this puzzle is to realize that, though steel may be cheap, the energy storage component of a flywheel is not. From basic principles it is possible to understand the relative capabilities of the materials used for flywheels. Materials for a composite flywheel cost roughly $50/lb as fabricated. The energy density of composites in a wheel is approximately 80 Wh/lb, which corresponds to a materials cost of $700/kWh. Steel costs $0.50/lb raw and approximately $2/lb fabricated. Several flywheels operate at about 0.93 Wh/lb (0.56 kWh/600 lb), resulting in a materials cost of $2160/kWh. This however is just the beginning of the story. There are additional costs for containment, vacuum systems, support, bearing systems, etc., and the steel flywheels are more than 50 times heavier per unit of stored energy than the composite flywheel. Unfortunately, though armed with this concept, there is not enough information to calculate the cost of the energy and power related components of the system from first principles.

The approach used here is to take known costs of complete systems and to use the relatively well-known costs of the PCS to extract the energy related cost. This approach was used for several different commercial wheels. The cost of the generator on the flywheel and the converter from variable frequency output to DC is assumed to be about $200/kW. In addition, there is need for a converter from DC to 60-Hz AC. The total PCS and generation cost is assumed to be $300/kW. Subtracting this from total costs for several commercial flywheel systems leads to costs ranging from $30,000/kWh for systems with 2-MVA and 15-second capability to $80,000/kWh for a

400-kW system with a five-second capability. An intermediate value of $50,000/kWh is used for this study.

The parasitic loss for a flywheel depends to a great deal on the type of bearing used for its support. For example, the lowest value seen on any of the slow speed flywheels is 0.2% (or 0.002 kW/kW-delivered) for the converter and another 0.2% for the bearings and enclosure. Operating costs are quite small on the wheels, and are generally included in a service contract that amounts to about $5/kW per year. These flywheels are expected to have 20 or more years of service. However, some bearing systems and vacuum components may have to be replaced on a fixed schedule, for example, every three years. The expected cost for this activity is relatively small, and is included in the O&M cost.

2.3.5 High Speed Flywheels for Power Quality

The costs of high-speed, generally composite flywheels were found to be quite variable, depending on the manufacturer. For the high-speed system described earlier in the DG section, costs are essentially the same for the PQ application as for DG, i.e., $300/kW for the PCS and $1000/kWh for the 15-minute storage unit. Other flywheels have been optimized for shorter discharge times. One such system has PCS costs of $333/kW and energy-related costs of $24,000/kWh-delivered. Another has PCS costs of $300/kW and energy-related costs of $125,000/kWh-delivered. All three types of high-speed flywheels for power quality are included in the life-cycle cost analysis because no system could be deemed "generic."

The parasitic losses for flywheels in a power quality system include both bearing or windage losses and continuous losses associated with forward voltage drop through the silicon-based components because the converter must be in the circuit continuously. Thus, parasitic losses are greater for power quality systems than for DG systems.

2.3.6 Micro-SMES and D-SMES

Superconducting Magnetic Energy Storage (SMES) has been designed for all three application categories discussed in this study. However, it has only been actually manufactured as a product for power quality and distribution stability applications. The 1-MJ/1-MW system developed by American Superconductor was sold to about a dozen industrial or commercial end users, primarily to prevent voltage sags or momentary outages from shutting down sensitive equipment. This PQ-SMES product is no longer being sold for this purpose because some of the other technologies have proved less expensive or easier to use. However, the American Superconductor product has evolved into a system called D-SMES that is being installed in multiple networked units for volt-amp reactive (VAr) control on distribution systems. These systems provide very little real power and operate for only very short periods (<1 second). Thus, the component costs have been reduced because thermal control is not an issue. The costs used in this part of the study are based on current D-SMES system costs: $50,000/kWh-delivered and $200/kW for the PCS. The efficiency is very good at 0.95, but the parasitic energy requirement (to operate the refrigerator) is relatively high at 0.01-kW/kW-delivered.

2.4 Power Conversion System Costs

The data in Tables 3 and 4, which were generated by Harshad Mehta of Silicon Power for this project, are the result of a separate analysis that compares the costs of power conversion systems for different energy storage technologies. “First Unit” and "Tenth Unit" costs are presented. The most significant difference between long-term and short-term PCS operation is the need for thermal control. This drives the cost up for long-term operation. Though the costs seem reasonable for the various technologies, the true value of the comparisons in these tables is that all of the technologies get the same consideration. As a result, when looking to the future, the relative costs are most important as a scale between the different technologies. One caveat here is that the numbers have not been verified by the authors of this report. Some items may be missing in the criteria for the various technologies, and if changes are required, it seems most likely that slight cost increases for all technologies may be appropriate before using the values in these tables. Tables 3 and 4 are presented as an illustration of trends in PCS costs. However, where actual values of PCS costs were available for specific technologies, these actual values were used in the analysis for this study.

2.5 Cost Tables

The cost and performance data for all the technologies analyzed in this study are presented in Tables 5, 6, and 7. Table 5 lists values for bulk energy storage technologies, Table 6 for DG technologies, and Table 7 for PQ technologies. These values were used in the analysis presented in sections 3 and 4. Note that in Table 5 there is no column for parasitic losses. This is because losses are negligible for bulk storage systems operated on a daily basis. Any losses are included in the system efficiency.

Table 3. PCS Costs for Long-Term Operation (e.g., Peak Shaving, Sustained Outages)

Technology	250 kW		1 MW		5 MW		20 MW	
	1st unit	10th unit	1st unit	10th unit	1st unit	10th unit	1st unit	10th unit
Flywheel	500	225	300	175	200	150	150	125
Battery	500	225	300	175	200	150	150	125
SMES	550	250	350	200	250	175	200	150
Note: Power rating is based on continuous operation. Note: All costs are in $/kW.								

Table 4. PCS Costs for Short-Term Operation, 0 to 30 seconds (e.g., Power Quality applications)

Technology	250 kW		1 MW		5 MW		20 MW	
	1st unit	10th unit	1st unit	10th unit	1st unit	10th unit	1st unit	10th unit
Flywheel	350	150	200	175	140	100	100	90
Battery	350	150	200	175	140	100	100	90
SMES	400	175	250	200	190	125	150	115
Note: All costs are in $/kW.								

Table 5. Characteristics of Bulk Energy Storage Technologies Used in Cost Analysis

Technology	Energy-Related Cost	Power– Related Cost	Balance of Plant	Efficiency (AC to AC)	Replacement Cost	Replacement Frequency	Fixed O&M
	($/kWh)	($/kW)	($/kWh)		($/kWh)	(yr)	($/kW-yr)
Lead-acid Batteries (Flooded Cell)	150	125	150	0.75	150	6	15
Lead-acid Batteries (VRLA)	200	125	150	0.75	200	5	5
Ni/Cd	600	125	150	0.65	600	10	5
Regenesys®	100	275	50	0.65	$150/kW	10	15
High Temp Na/S	250	150	50	0.7	230	10	20
Compressed Air Energy Storage (CAES)	3	425	50	0.73	0	None	2.5
Pumped Hydro	10	1000	4	0.75	0	None	2.5
Pumped Hydro Variable Speed	10	1050	4	0.78	0	None	2.5

Table 6. Characteristics of Energy Storage Technologies for DG Applications Used in Cost Analysis

Technology	Energy-Related Cost	Power–Related Cost	Balance of Plant	Efficiency (AC to AC)	Replacement Cost	Replacement Frequency	Parasitic Loss	Fixed O&M
	($/kWh)	($/kW)	($/kW)		($/kWh)	(yr)		($/kW-yr)
Lead-acid Batteries (Flooded Cell)	150	175	50	0.75	150	6	0.1 %/day	15
Lead-acid Batteries (VRLA)	200	175	50	0.75	200	5	0.1 %/day	5
Ni/Cd	600	175	50	0.65	600	10	Not known	25
Zn/Br	400	175	0	0.60	100	8	0.01 %/hr	20
Na/S	250	150	0	0.7	230	15	0.05%/day	20
Li-Ion	500	175	0	0.85	500	10	0.01 %/hr	25
V-redox	600	175	30	0.7	600	10	0.2%/day	20
CAES-surface	120	550	50	0.79	0	None	None	10
Flywheels (high-speed) 18 kW, 37 kWh	1,000	300	0	0.95	0	None	0.05%/hr	$1000/yr
Hydrogen fuel cell	15	1500	0	0.59	$100/kW	6	None	3.8
Electrolyzer (to accompany fuel cell or engine)	None	300	None	0.9	$50/kW	6	None	Not known
Hydrogen engine	15	300	0	0.44	$100/kW	10	None	2.5
Note: The kW and kWh parameters in the first column are included only for FES because the costs are specific to those systems and are not generic.								

Table 7. Characteristics of Energy Storage Technologies for PQ Applications Used in Cost Analysis

Technology	Energy- Related Cost (delivered)	Power-Related Cost	Efficiency (AC to AC)	Replacement Cost	Replacement Frequency	Parasitic Loss Converter	Parasitic Loss Storage	Fixed O&M
	($/kWh)	($/kW)		($/kWh)	(yr)	(kW/kW)	(kW/kW)	($/kW-yr)
Lead-Acid Batteries	300	250	0.75	300	6	0.002	0.00001	10
Li-Ion	500	200	0.85	500	10	0.002	0.0001	10
Micro-SMES	50,000	200	0.95	0	None	0.002	0.01	10
Flywheels (high-speed) 150 kW for 15 min.	1,000	300	0.95	0	None	0.002	0.0005	5
Flywheels (high-speed) 120 kW for 20 sec.	24,000	333	0.95	16,000	16	0.002	0.0005	5
Flywheels (high speed) 200 kW for 20 sec.	125,000	300	0.95	0	None	0.002	0.002	5
Flywheels (low-speed)	50,000	300	0.9	0	None	0.002	0.002	5
Supercapacitors	30,000	300	0.95	0	None	0.002	0.0001	5

Note: The kW parameters in the first column are included only for FES because the costs are specific to those systems and are not generic.

2.6 Commercial Maturity

Although many technologies are discussed in this report, they are not all at the same level of technical or commercial maturity. Figure 4, which has been updated from the previous report, attempts to describe the maturity of the technologies and relates the authors' certainty in the cost data. For the CAES system, the power train costs are more certain than the storage costs, which must be determined for each project. Since the system cost is dominated by the power-related cost, the system cost certainty is listed as “quotes available.”

Figure 4. Commercial Maturity and Cost Certainty for Energy Storage Technologies

Technology	Commercial Maturity	Cost Certainty
Lead-Acid Batteries	◆	◆
Regenesys®	■	■
Na/S Batteries	■	■
Ni/Cd Batteries	▲	■
Zn/Br Batteries	■	▲
Li-ion Batteries	■	●
Vanadium-redox Batteries	■	■
Superconducting Magnetic Energy Storage (D-SMES)	▲	▲
Flywheel (high-speed)	■	■
Flywheel (low-speed)	▲	◆
Supercapacitor	■	■
Compressed Air Energy Storage (CAES)	■	▲
Compressed Air Energy Storage in surface vessels (CAES-surface)	●	●
Pumped Hydro	◆	◆
Fuel Cells (hydrogen)	■	■
Hydrogen combustion engine	▲	◆

Legend for Figure 4

Symbol	Commercial Maturity	Cost Certainty
◆	Mature products, many sold	Price list available
▲	Commercial products, multiple units in the field	Price quotes available
■	Prototype units ordered, under construction, or in the field	Costs determined for each project
●	Designs available, nothing built	Costs estimated

3 Life-cycle Cost Analysis

3.1 Methodology

A life-cycle cost comparison was performed on all of the technologies. On this basis, differences in efficiency, replacement frequency, and operational factors were also taken into account. The life-cycle cost analysis follows a standard economic format. [6] The results can be computed as levelized annual cost, in \$/kW-yr; or as a revenue requirement, in ¢/kWh. Levelized annual cost is what a system operator would expect to pay yearly for all operations of the energy storage system, including repaying a loan and interest for the up-front capital cost. "Levelized" means the amount has been adjusted to account for future costs at assumed discount, escalation, and inflation rates.

Levelized annual cost can be calculated as \$/kW-yr and converted to revenue requirements (¢/kWh) using the assumed number of hours operated per year. The revenue requirement is the amount, in ¢/kWh, that an energy provider, such as a utility, would need to charge for each kWh of energy delivered, to cover all costs for operating and owning the system. The revenue requirement value is most applicable for utilities that expect to sell the energy generated, or for large end-users who want to avoid expensive on-peak energy costs. It is not appropriate for power quality systems, which may operate for a few minutes in a single year.

The levelized annual cost (LAC) is defined as:

LAC (\$/kW-yr) = carrying charge for capital equipment
+ levelized fixed O&M costs
+ levelized annual costs for replacement parts
+ levelized variable costs for energy and O&M

The calculation of LAC was performed as follows:

$$\text{LAC (\$/kW-yr)} = \text{FCR} * \text{TCC} + \text{OMf} * \text{Lom} + \text{ARC} * \text{Lom} + [\text{OMv} * \text{Lom} + \text{UCg} * \text{HR}*10^{-6} * \text{Lg} + \text{UCe} * (1/\eta) * .01*\text{Le}] * \text{D} * \text{Ho} \quad (2a)$$

where:

FCR	=	Fixed Charge Rate or Carrying Charge Rate (1/yr)
TCC	=	Total Capital Cost per kW of Power Output (\$/kW)
ARC	=	Annualized Replacement Costs
OMf	=	Fixed O&M Costs (\$/kW-yr)
OMv	=	Variable O&M Costs (¢/kWh)
Lom	=	Levelization Factor for O&M Costs (a function of I and Y)
UCg	=	Unit Cost of Natural Gas (\$/MBtu)
HR	=	Heat Rate (Btu/kWh)
Lg	=	Levelization Factor for Gas (a function of I and Y)
UCe	=	Unit Cost of Input Electricity (¢/kWh)
η	=	Storage Efficiency (kWh_{out}/kWh_{in})
Le	=	Levelization Factor for Electricity (a function of I and Y)
Ho	=	Operating Time per Day (hr/d)
D	=	Operating Days per year (d/yr)
I	=	Discount Rate (1/yr)
Y	=	Levelization Period or System life (yr)

Revenue requirement (RR) is calculated as follows:

RR (¢/kWh) = LAC ($/kW-yr) * 100 (¢/$) / [Ho (hr/day) * D(days/yr)] (2b)

The levelization factors convert present and future costs to annual costs on the basis of an assumed discount rate and levelization period. These factors are similar to a capital recovery factor, but also take into account differences between the real and apparent escalation rates and the discount and inflation rates.

3.2 Capital Cost Components

From equation 2a, it is clear that the capital cost is an important component of the annual cost. The detailed calculation of these costs was described in the previous report. [1] For those systems that consist of an energy storage unit and a single power conversion system that operates in both the discharge and charge modes, the system capital cost is the sum of the component costs plus BoP costs:

$$Cost_{total}\ (\$) = Cost_{pcs}\ (\$) + Cost_{storage}\ (\$) + Cost_{Bop}\ (\$) \qquad (3)$$

Hydrogen system costs are developed somewhat differently, as described in the previous report. For most systems, the cost of the PCS is proportional to the power rating:

$$Cost_{pcs}\ (\$) = UnitCost_{pcs}\ (\$/kW) \times P\ (kW) \qquad (4)$$

where P is the power rating.

For many systems, the cost of the storage unit is proportional to the amount of energy stored:

$$Cost_{storage}\ (\$) = UnitCost_{storage}\ (\$/kWh) \times E\ (kWh) \qquad (5)$$

where E is the stored energy capacity.

In the simplest case, E is equal to P × t, where t is the discharge time.

There are some exceptions and constraints to these simple equations. To begin with, all systems have some inefficiency. To account for this, Equation 5 is modified as follows:

$$Cost_{storage}\ (\$) = UnitCost_{storage}\ (\$/kWh) \times (E\ (kWh) / \eta) \qquad (6)$$

where η is the system efficiency (AC to AC).

In addition, many storage units are not discharged completely in operation because of voltage or mechanical considerations. In these cases, the storage unit must be oversized; the unit cost must then reflect $/kWh-delivered.

Also, for some technologies, the unit cost is not a constant over the range of sizes (i.e., economies of scale prevail). This is especially true for SMES where the unit energy cost scales approximately with $E^{2/3}$. Finally, for lead-acid batteries, Li-ion batteries, and some flywheels, the unit energy costs do not hold for short discharge times, because it is generally not possible to get all the energy out in a short pulse. Thus, the smallest batteries considered in this study were rated at the ten-minute discharge rate.

The balance-of-plant costs, $Cost_{Bop}$, are typically proportional to energy capacity, but in some cases are fixed costs or proportional to power rating. In this study, building costs were included for bulk energy storage systems, assuming a new site was likely to be needed for such large plants. For DG systems, we assumed that smaller units would be located at existing substations, and hence building costs were not included. Power quality products are usually offered as self-contained units and again, building costs were not included.

Table 8. Economic Parameters for Life-Cycle Cost Analysis

Parameter	Value
General inflation rate	2.5%
Discount rate	8.5%
Levelization period	20 years
Carrying charge rate	12%
Fuel cost, natural gas	5 $/MBTU
Fuel cost escalation rate	0%
Electricity cost	5 ¢/kWh
Electricity cost escalation rate	0%
O&M cost escalation rate	0%

3.3 Economic Assumptions

The analysis requires economic assumptions in addition to the cost and performance parameters for each technology. The economic assumptions are listed in Table 8. The escalation rate for fuel, electricity, and O&M was assumed to be zero, meaning that these elements have the same inflation rate as everything else, i.e., they do not escalate in price faster than the general inflation rate. Note also that the levelization period of 20 years implies a system life of 20 years. This has implications for replacement costs, as discussed below. The sensitivity of the results to these assumptions will be examined in a follow-on study.

3.4 Operating Assumptions

Operating parameters include hours per day of discharge operation and number of days of operation per year. For this analysis, it was assumed that the storage unit discharges once per day and that the system operated 250 days per year (i.e., five days/week, 50 weeks/year). For purposes of the calculations, power quality systems were also assumed to operate once per day. While this may be unrealistic, the amount of energy used for recharging is so small as to be negligible. The discharge time (and corresponding storage capacity) were parameters of the analysis. For all technologies except hydrogen systems with a separate electrolyzer, the recharge time was assumed equal to the discharge time. Electrolyzers were sized to recharge during the hours when the fuel cell or engine system is not actively discharging (i.e., 24-t).

3.5 Replacement Costs

One motivation for investigating life-cycle costs is to be able to include replacement costs in an annual budget. Up-front capital costs do not tell the whole story for many storage technologies because they have limited lifetimes or cycle lives. Some batteries are short-lived compared to other technologies. This aspect of technology performance needs to be compared with other systems that do not require significant replacement costs during a 20-year lifetime.

The replacement costs were considered as part of fixed O&M in the earlier study. Here they are called out separately. Table 9 indicates the frequency of replacement for the different technologies and the cost of the replacement parts.

Table 9. Replacement Assumptions for Energy Storage Technologies

Technology	Replacement Period (Years)	Replacement Costs ($/kWh)
Lead-acid battery, flooded (bulk, DG)	6	150
Lead-acid battery, VRLA (bulk, DG)	5	200
PQ battery (lead-acid)	6	300
Ni/Cd (bulk, DG)	10	600
Regenesys	10	150 ($/kW)
Na/S (bulk)	10	230
Na/S (DG)	15	230
Zn/Br (bulk, DG)	8	100
Li-ion (DG, PQ)	10	500
V-redox (DG)	10	600
CAES, CAES-surface	30	0
Pumped hydro	30	0
High speed flywheel (DG, PQ)	20	0
High speed flywheel (PQ)	16	16,000
Low speed flywheel (PQ)	20	0
SMES (PQ)	20	0
Supercapacitors (PQ)	20	0
Hydrogen fuel cell (DG)	6	100 ($/kW)
Electrolyzer (DG)	6	50 ($/kW
Hydrogen engine (DG)	10	100 ($/kW)

In the life-cycle cost analysis, future expenditures are converted to annual costs assuming the funds for future replacement purchases could be saved at the current interest rate:

$$A = F * \{(1+I)^{-n} + (1+I)^{-2n} + .. \} * \{ I * (1+I)^{m} / [(1 + I)^{m} - 1]\} \qquad (7)$$

where A is the annual amount in $/kWh, F is the future amount in $/kWh, I is the discount rate, n is the year of replacement, and m is the number of years of service (equal to 20 in this study). The first factor has only as many terms as the number of replacements. This annual amount is then included in the equation for annual costs.

3.6 Parasitic Energy Requirements

Most of the energy storage systems described in this report require some on-going electrical support to keep running, even when not in either charge or discharge mode. This is to make up for operating losses or to maintain temperature. One example is a flywheel that requires continuous electric power to run vacuum pumps to maintain a vacuum in the flywheel container. Another is the trickle charge required by some batteries. Yet another is power to a SMES refrigeration system to maintain cryogenic conditions at the magnet. Some of these can be interrupted, but will normally be operated continuously.

For the large bulk storage systems that operate in both charge and discharge mode for many hours every day, this loss becomes part of the overall system inefficiency and is not computed separately. For DG systems that may operate for less than an hour a day, it is necessary to account for these loads and energy expenses. For power quality systems connected directly to the end-user's bus, power must flow at all times through the PCS. Although the loss is small (about 0.2% of power rating), it must still be accounted for, in addition to other system parasitic energy requirements. Table 10 lists the assumptions for parasitic losses used in this study.

Table 10. Parasitic Losses for DG and PQ Energy Storage Technologies

Technology	Electricity Requirement % Stored per Day	Loss Mechanism
Lead-acid battery, flooded (DG)	0.1	Trickle charge
Lead-acid battery, VRLA (DG)	0.1	Trickle charge
Ni/Cd (DG)	0	Insignificant
Na/S (DG)	0.05	Heating
Zn/Br (DG)	0.24	Flow losses
Li-ion (DG)	0.24	Trickle charge
V-redox (DG)	0.2	Flow losses
High speed flywheel (DG)	1.25	Bearing losses, windage
	Electricity Requirement kW/kW–Delivered	
PQ battery (lead-acid)	0.002	PCS losses, trickle charge
Li-ion battery (PQ)	0.002	PCS losses
High speed flywheel (PQ)	0.002-0.004	PCS losses, bearing losses
Low speed flywheel (PQ)	0.004	PCS losses, bearing losses
SMES (PQ)	0.012	PCS, refrigeration
Supercapacitors (PQ)	0.002	PCS losses
Note: Losses for bulk energy storage technologies are accounted for in their efficiencies.		

4 Results

Results are presented in this section for all three application categories. For Bulk Storage and DG, results are presented both as an annual cost ($/kW-yr) and as revenue requirements (¢/kWh). Note that the comparison of technologies is the same in either presentation, i.e., results appear in the same order when calculated either way. One result may simply be more interesting or more meaningful to different users. Power Quality results are presented only as $/kW-yr, as they are dominated by capital costs.

Cost components (i.e., capital carry charge, fuel, electricity, O&M, and replacement costs) are also shown for selected cases.

4.1 Bulk Energy Storage Systems

4.1.1 Annual Cost

Levelized annual cost projections for bulk energy storage technologies are shown in Figure 5. CAES is shown to be the least expensive technology, followed by pumped hydro. This is primarily because of the low cost of storage. Pumped hydro with variable speed drive is slightly more expensive than conventional pumped hydro, even though it is more efficient. This is offset by large benefits due to greater operational flexibility.

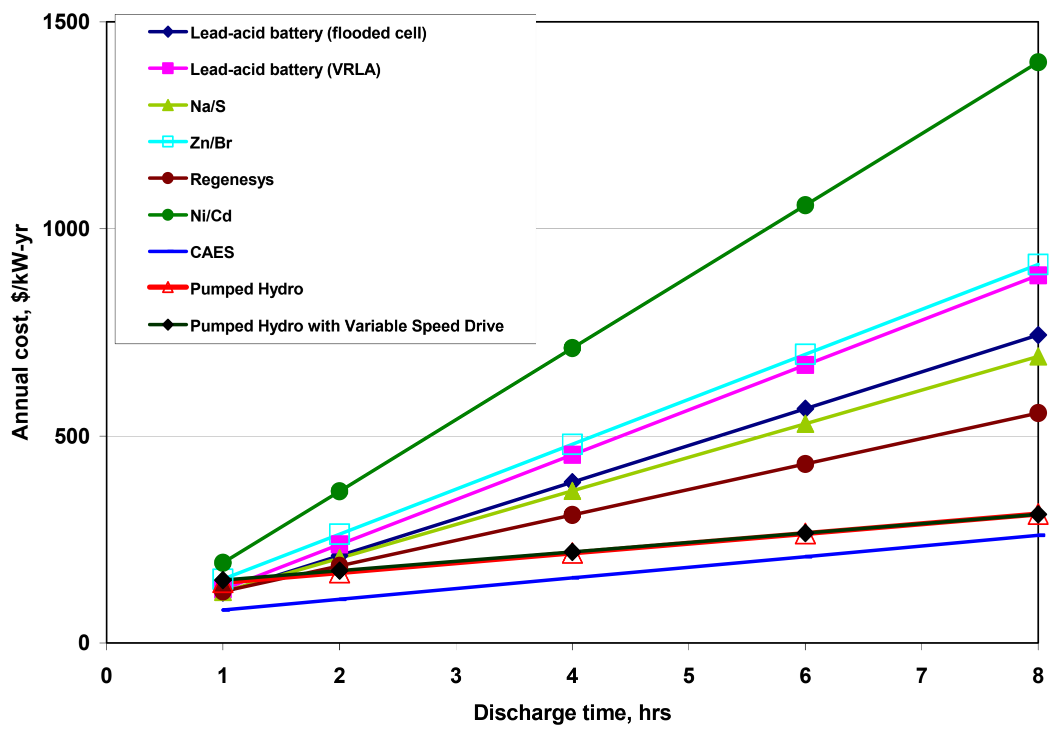

Figure 5. Levelized Annual Cost for Bulk Energy Storage Technologies (10-1000 MW).

4.1.2 Revenue Requirements

Revenue requirements for bulk energy storage systems are shown in Figure 6. These represent the cost of the energy served, or the minimum price for energy that would cover all expenses to generate that energy. The costs all decrease for larger systems. Note that even the lowest cost of about 14¢/kWh is significantly larger than the average cost of input electricity, 5¢/kWh.

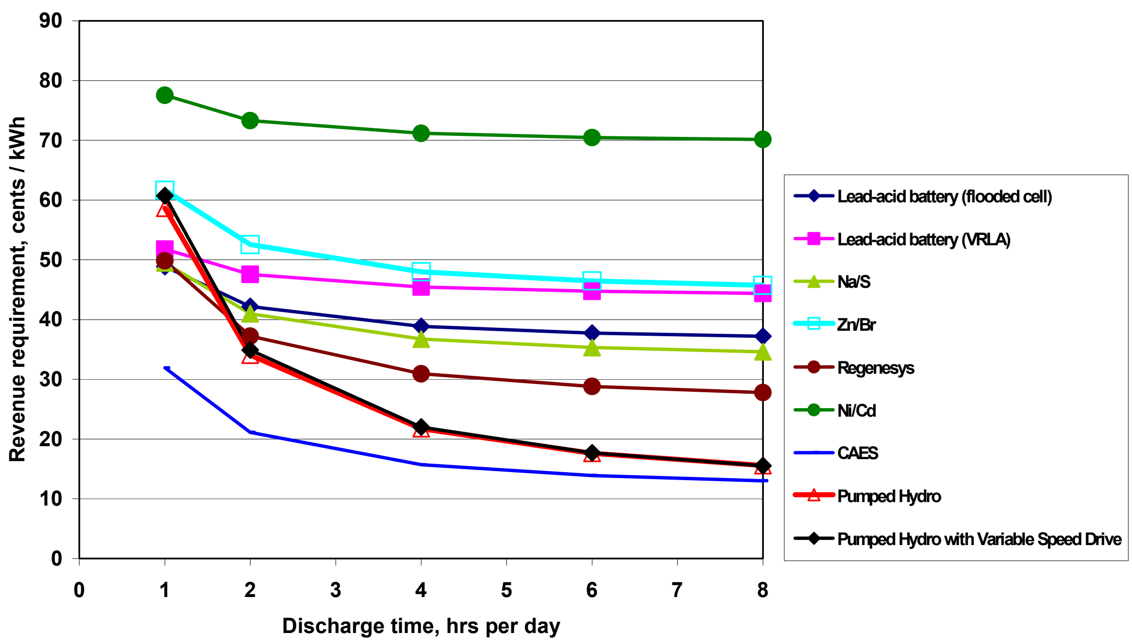

Figure 6. Revenue Requirement for Bulk Energy Storage Technologies (10-1000 MW).

Not surprisingly, CAES and pumped hydro are especially attractive for bulk energy storage. However, since sites for these systems are extremely hard to find, it is interesting to look to the next most cost-effective system, and this is Regenesys.

4.1.3 Cost Components for Eight-hour Systems

The components of the annual costs for an eight-hour system are shown in Figure 7.

While dominated by capital cost, there are still some other interesting differences between the technologies. For example, all the battery systems have replacement costs, but CAES and pumped hydro do not. The Regenesys costs are much less than those for other battery systems.

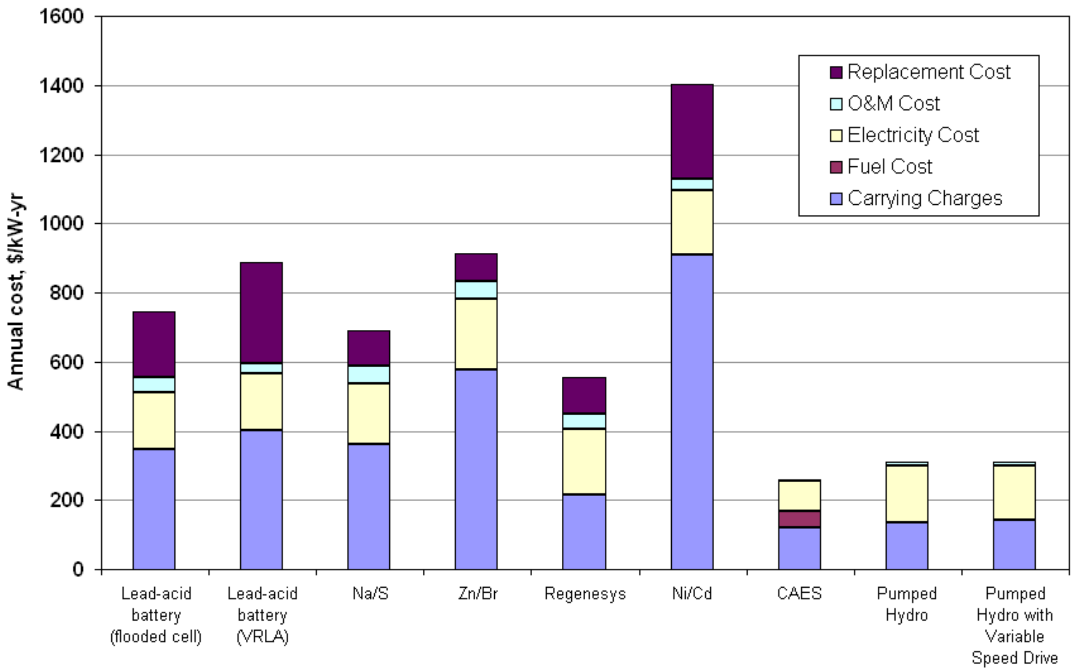

Figure 7. Components of Annual Cost for Bulk Storage Technologies (8-hour discharge).

4.2 Distributed Generation Systems

4.2.1 Annual Cost

The levelized annual cost for DG energy storage is shown in Figure 8. At short discharge times, the costs are similar for all systems except the hydrogen fuel cell, which is more expensive. With increasing storage time, the curves diverge. The hydrogen fuel cell curve has a very different slope from the other technologies because the storage cost component is so small compared to the power-related costs for the fuel cell and electrolyzer. Thus, there is little increase in system cost with storage time. At about two hours of storage, the hydrogen fuel cell begins to look more attractive. Two other technologies are surprisingly attractive. First is CAES in surface vessels. Although such systems are not actually being built, there are conceptual designs that might prove commercially interesting. Second, the Na/S battery looks very attractive in this application. One reason is the long lifetime, which will be highlighted in a later section.

4.2.2 Revenue Requirements

The revenue requirements shown in Figure 9 are for relatively small DG systems. Electricity produced by these systems would need to be sold at or above the minimum cost to make a profit. Here the least expensive energy is about 25¢/kWh and many systems are generating energy at more than 50¢/kWh. Only in unusual peaking situations would energy at this price be cost-effective.

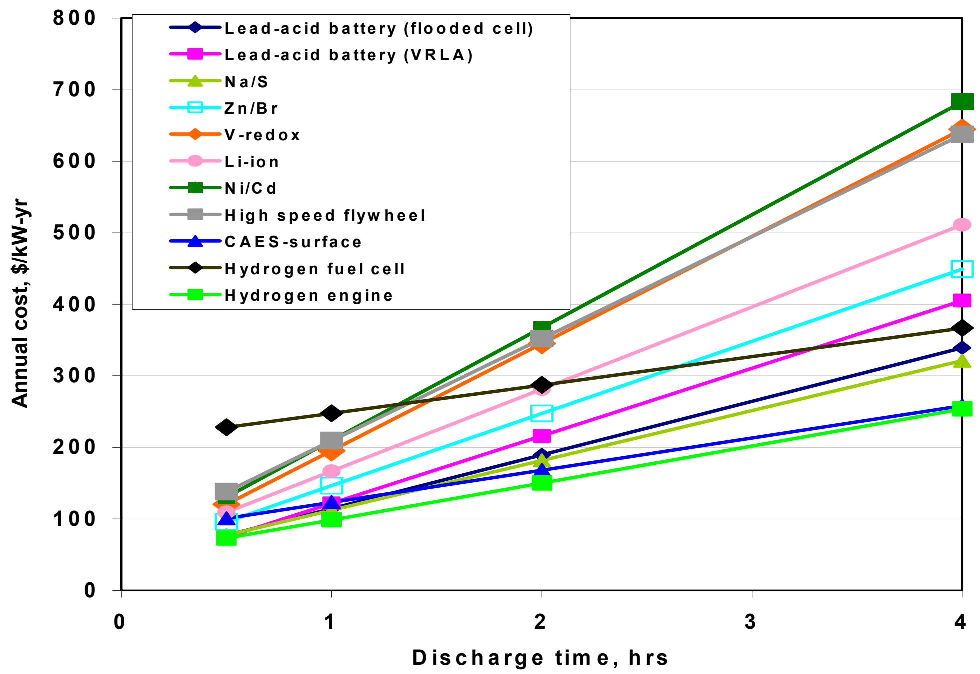

Figure 8. Levelized Annual Cost for DG Systems (100 kW-2 MW).

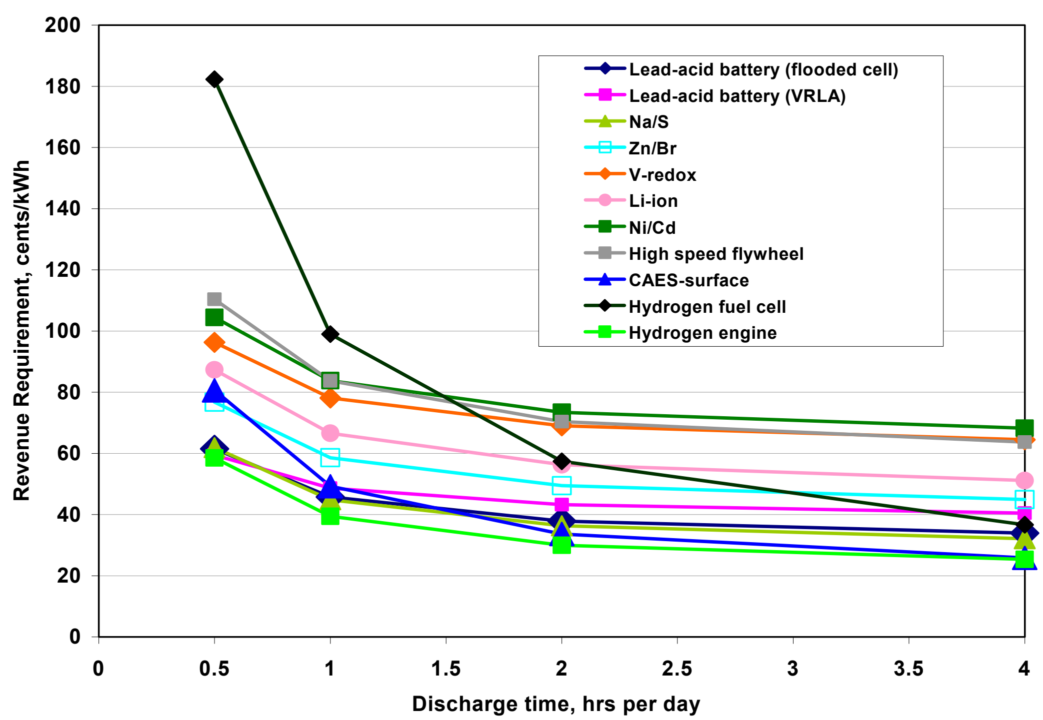

Figure 9. Revenue Requirements for DG Technologies.

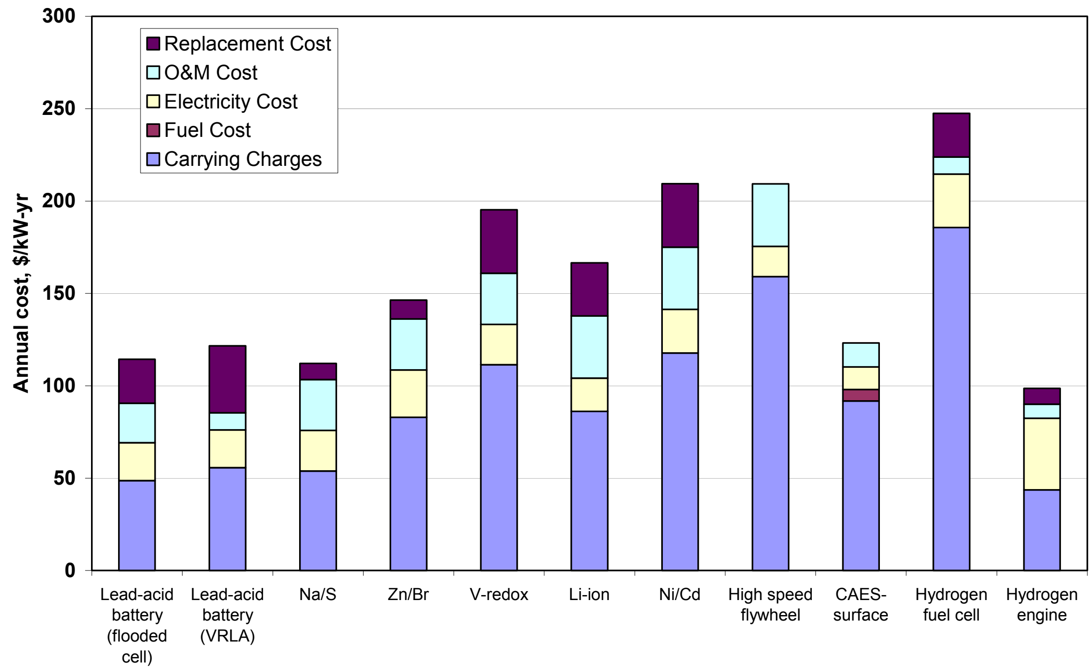

Figure 10. Components of Annual Cost for DG Technologies (1-hour discharge).

4.2.3 Cost Components for One- and Four-Hour Systems

Cost components for one-hour DG systems are shown in Figure 10. Note that the Na/S battery has very small replacement costs because it is a 15-year system. This is a distinct advantage over the other battery types. The two hydrogen storage technologies require substantial electrical input because they are the least efficient. The cost components for four-hour systems are shown in Figure 11. Here the fuel cell system is competitive.

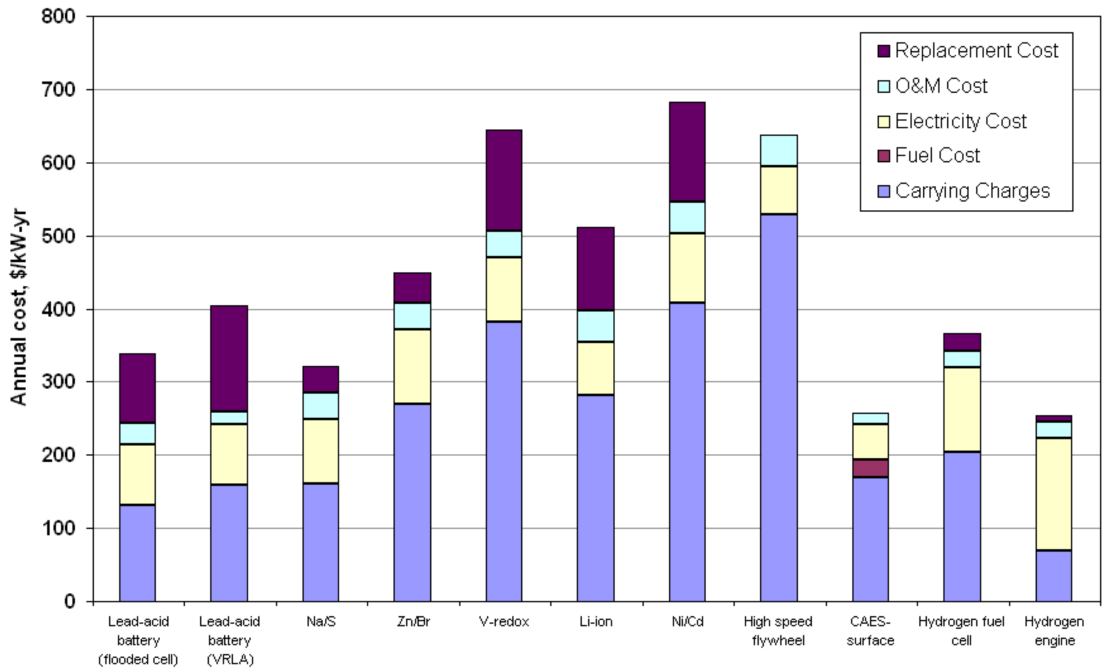

Figure 11. Components of Annual Cost for DG Technologies (4-hour discharge).

4.3 Power Quality Systems

Power quality systems were compared for the range of discharge periods from one to thirty seconds. This encompasses the design specifications for these systems. The results include three different high-speed flywheel systems, as shown in Figure 12. The three are quite different in cost as one is designed for longer output, and the other two are optimized for a 20-second output. It is not possible to show a "generic" high-speed flywheel system.

The Li-ion system is included and shown as the “advanced battery.” Even though it has not been proposed for power quality applications, it seems to fit well here, based on projected system costs.

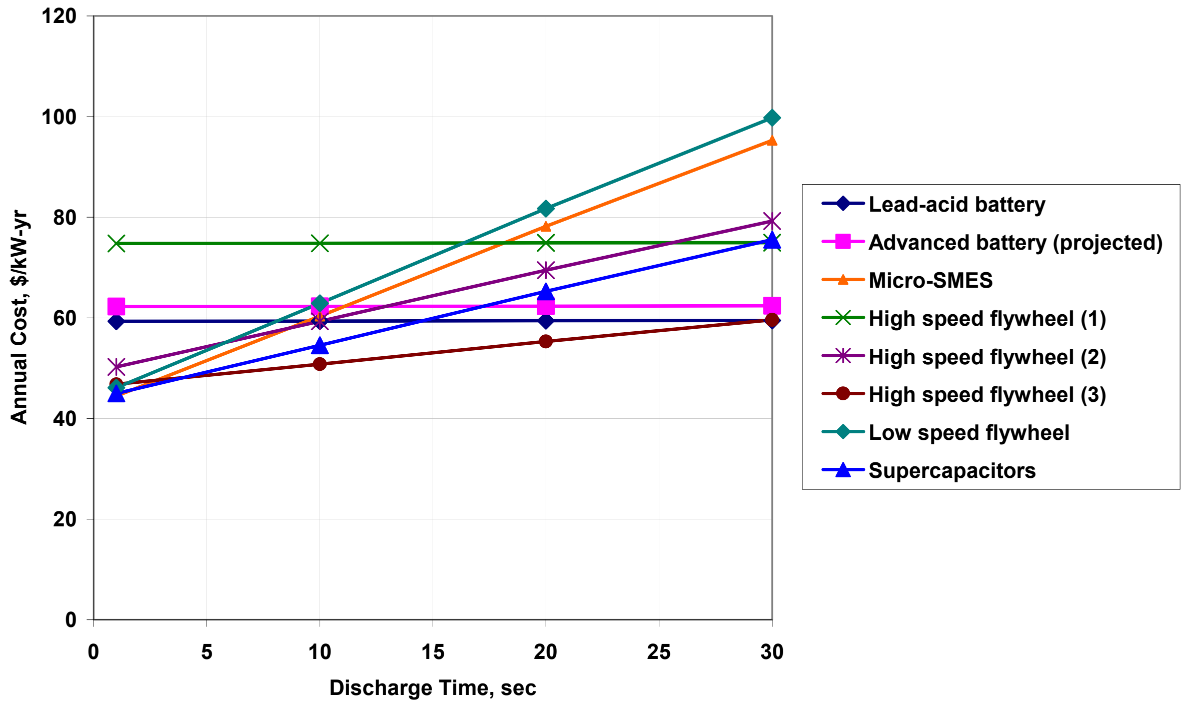

Figure 12. Levelized Annual Cost for Power Quality Technologies (100 kW - 2 MW).

4.3.1 Cost Components for One-Second Systems

The early power quality systems, especially micro-SMES, were designed for just one second of power discharge. The pulsed power system met the majority of needs for voltage sag and momentary outage protection. The components of annual cost for one-second systems are shown in Figure 13. All technologies are dominated by capital cost. As shown in Figure 13, and also previously in Figure 12, micro-SMES and supercapacitors are particularly attractive for one-second discharges. Lithium-ion batteries also have potential for this application because of the potential for long life.

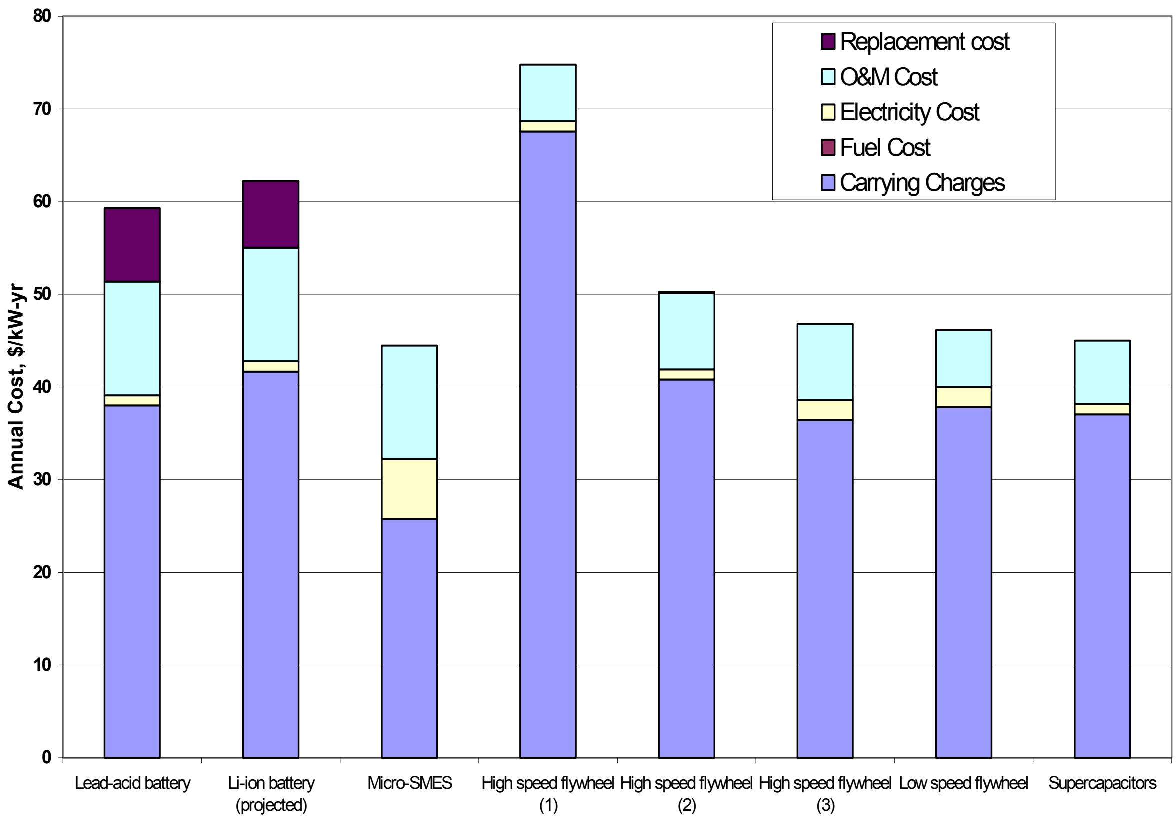

Figure 13. Components of Annual Cost for Power Quality System (1-second discharge).

4.3.2 Cost Components for 20-Second Systems

Battery systems and some flywheels can be optimized for greater storage capacity. A battery sized for one-second of discharge is the same as a battery sized for 20 or 30 seconds of discharge. This is not true for micro-SMES or supercapacitors. So the comparison changes dramatically for 20-second systems, as shown in Figure 14. Note also that the cost of a SMES system increases due to the large electrical power requirement for refrigeration.

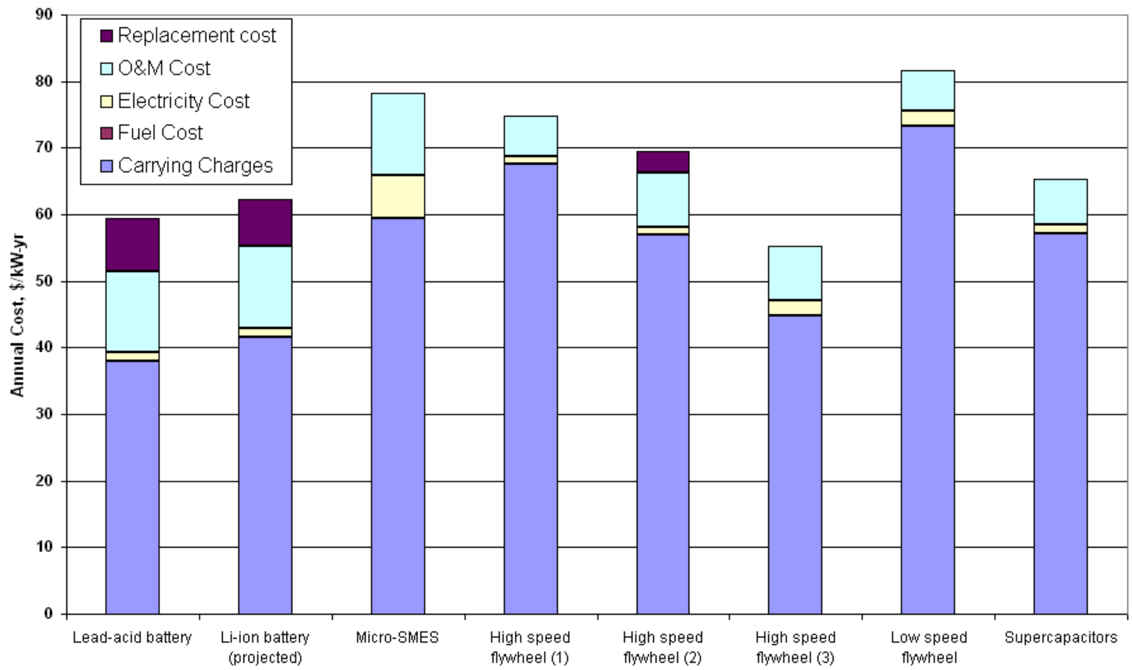

Figure 14. Components of Annual Cost for Power Quality Systems (20-second discharge).

5 Conclusions and Recommendations

Some conclusions from this study include:

- Batteries (of one type or another) can address all application areas, although they are not always the least expensive option.
- Replacement costs factor significantly into the life-cycle costs of batteries, much more so than other technologies. This factor also shows a distinct difference between battery types.
- CAES is very cost-effective for bulk energy storage and CAES-surface has potential for DG with the development of storage vessel technology.
- Flywheels are becoming available in a variety of types and with a range of capabilities, including some potential for DG.
- Power from systems consisting of hydrogen fuel cells and electrolyzers can only become attractive for DG applications with relatively long discharge times and with a reduction in capital costs.
- The life-cycle costs of power quality systems are dominated by capital and replacement costs. Other operating costs add little to the comparison.
- For power quality applications, the best choice is strongly dependent on the discharge time required. For a one- to two-second discharge, SMES and supercapacitors are attractive, whereas at 20- to 30-seconds, some flywheels or battery systems are less expensive.

The recommendations for additional analysis include:

- Perform additional sensitivity studies, evaluating the impact of varying input parameters such as electricity costs and interest rates.
- Investigate replacement periods and costs in greater detail, since they have a major impact on life-cycle cost. Consider cycle life in addition to calendar life.
- Add an application category that addresses a typical UPS function - a discharge duration of 30 seconds to 15 minutes.
- Consider additional economic factors such as taxes.
- Consider the siting issues and the cost of land due to varying system footprints.
- Revisit costs for surface CAES, since it appears particularly attractive. If literature is unavailable, consider an engineering study.
- Consider additional technologies, such as nickel-metal hydride batteries.

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A Appendix A. Comparison of Batteries and Fuel Cells

A.1 Objective

The purpose of this Appendix is to compare and contrast battery technologies and fuel cell technologies. Whereas both technologies can sometimes appear to be used in the same way, there are differences in both operation and suitable applications. There are also similarities. In fact, sometimes it is hard to say whether a technology is a battery or a fuel cell. This Appendix shows the spectrum of technologies (Figure A-1) and defines some common examples.

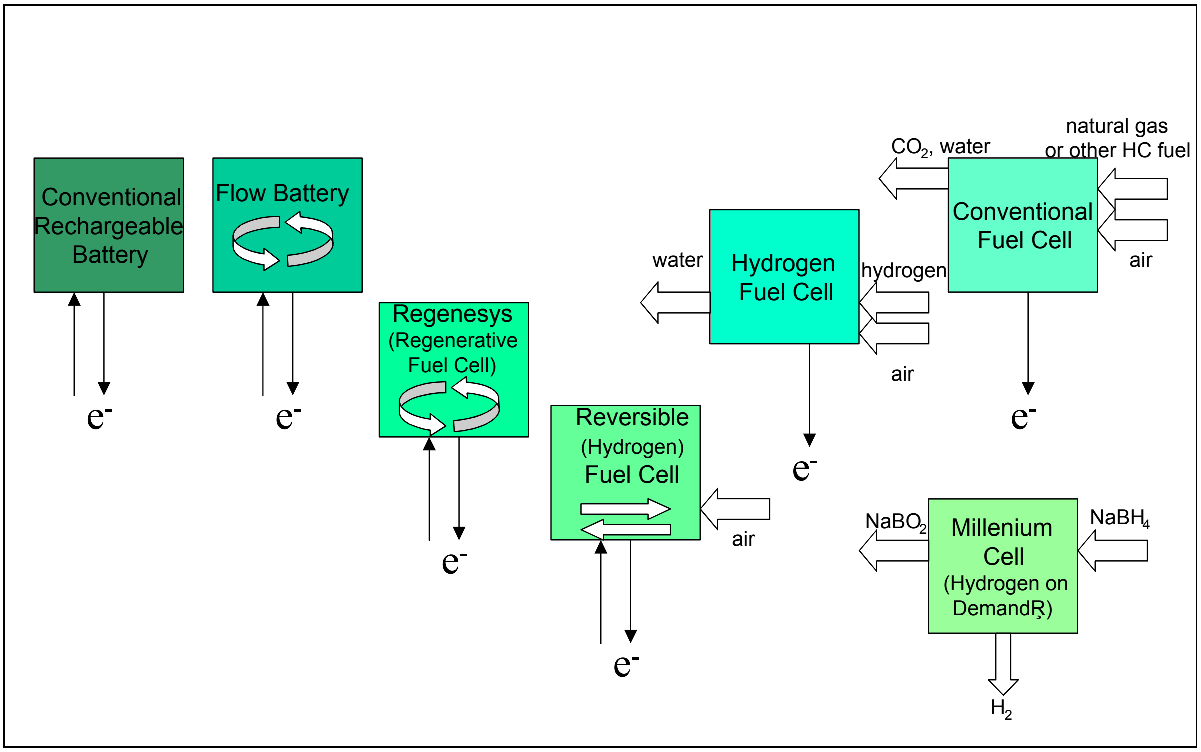

Figure A.1. Spectrum of Battery and Fuel Cell Configurations.

A.2 Introduction

A battery is defined as "a device that converts the chemical energy contained in its active materials directly into electrical energy by means of an electrochemical oxidation-reduction reaction." (Linden,1983).[A-1]

A fuel cell is "an electrochemical device that continuously converts the chemical energy of a fuel and oxidant to electrical energy." (Linden, 1983).

Thus, the technologies are similar in that electrochemistry provides electrons for an electric circuit. The simplest explanation of the difference between a conventional battery and a conventional fuel cell is, therefore, that a battery is a self-contained unit, whereas a fuel cell requires continuous fuel and oxidant input. When the reactants contained within a battery have been consumed, the battery must be replaced or

[A-1] David Linden, *Handbook of Batteries and Fuel Cells*, McGraw Hill, 1983 recharged. The fuel cell will operate as long as fuel and oxidant are supplied.

These differences seem straightforward enough, but recently a number of systems have been developed that blur the distinctions between batteries and fuel cells. For example, in so-called "flow batteries," the reactants are not contained within the same unit as the voltage stack, but in separate tanks that feed the power unit. And hydrogen fuel cell systems can be both limited by the hydrogen fuel supply, or made to operate in reverse, as in a rechargeable battery. These variations are shown in Figure A.1. and described in greater detail in the following section.

Another difference is that the reactants in a battery are normally a metal and a metallic oxide, whereas the reactants in a fuel cell are typically hydrogen and oxygen. There is some similarity in the electrolytes. The chemistry of the two technologies is described briefly in a later section.

A.3 Battery and Fuel Cell Configurations

A.3.1 Primary Battery

A primary battery is not rechargeable. It can be operated until the reactants are consumed. It must then be discarded in an environmentally safe manner.

A.3.2 Secondary Battery

A rechargeable battery is also called a secondary battery. Applying an electric current or voltage can reverse the direction of the reactions and thus "recharge" the battery. Energy is again stored in the chemical potential of the reactants. This is the most common type of rechargeable battery. Most consumer products with rechargeable batteries, such as laptop computers, cameras or remote control toys, use "conventional" rechargeable batteries. Most are either Lead-Acid, Nickel-Metal Hydride, Nickel/Cadmium, or Lithium-ion batteries. In "conventional" rechargeable batteries, the unit is self-contained and the only thing that flows in and out of the battery is electricity.

A generic rechargeable battery is shown in Figure A.2. In the charging mode, electricity is applied to the battery and ions flow in the opposite direction.

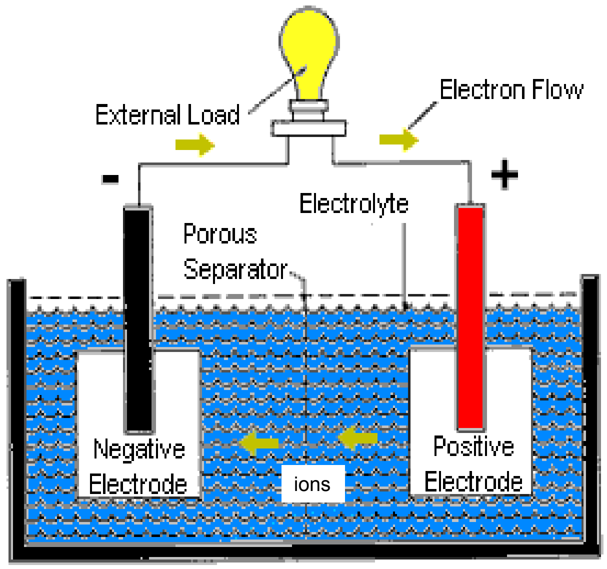

Figure A.2. Generic Rechargeable Battery Discharging.

A.3.3 Flow Batteries

"Flowing electrolyte batteries generally contain pumps, plumbing, electrolyte reservoirs, and electrochemical cell stacks. During charge and discharge operations, battery electrolyte is circulated through the cell stacks in which the electrochemical reactions take place. Charged species may be stored inside the stacks or in the reservoirs. Redox flow batteries are "those electrochemical systems where the oxidation and reduction of two chemical species take place on inert electrodes and these active materials are stored externally from the battery cell." (Linden, 1983) In operation, the reactants flow through opposite sides of a cell, separated by an inert separator. In such a system, the storage capacity is determined by the mass of reactants (as in all batteries), but the capacity is easily increased or decreased by changing tank sizes. Flow batteries are rechargeable, as the reactants are good for a minimum of 2000 cycles, and up to more than 10,000 cycles.[A-2] The overall battery system is also self-contained, i.e., from the users' point of view the only thing that flows in and out of the system is electricity.

Three common types of flow batteries are zinc/bromine batteries, vanadium-redox batteries, and the system called Regenesys®.

A zinc/bromine flow battery is shown in Figure A.3. The chemical processes are indicated. A vanadium-redox flow battery is shown in Figure A.4. In this battery, the two active species are vanadium in different states of oxidation. The Regenesys® system is described in greater detail below.

[A-2] C. Lotspeich, "A Comparative Assessment of Flow Battery Technologies," Proceedings 2002 EESAT Conference, San Francisco, California, April 2002

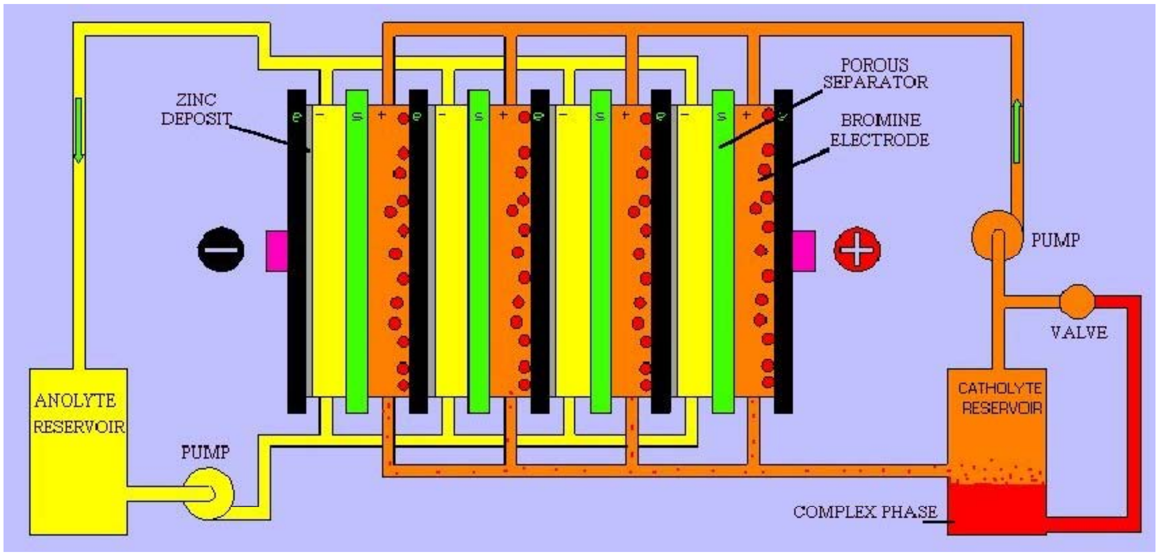

Figure A.3. Zinc/bromine Battery (Courtesy of ZBB Energy Corporation).

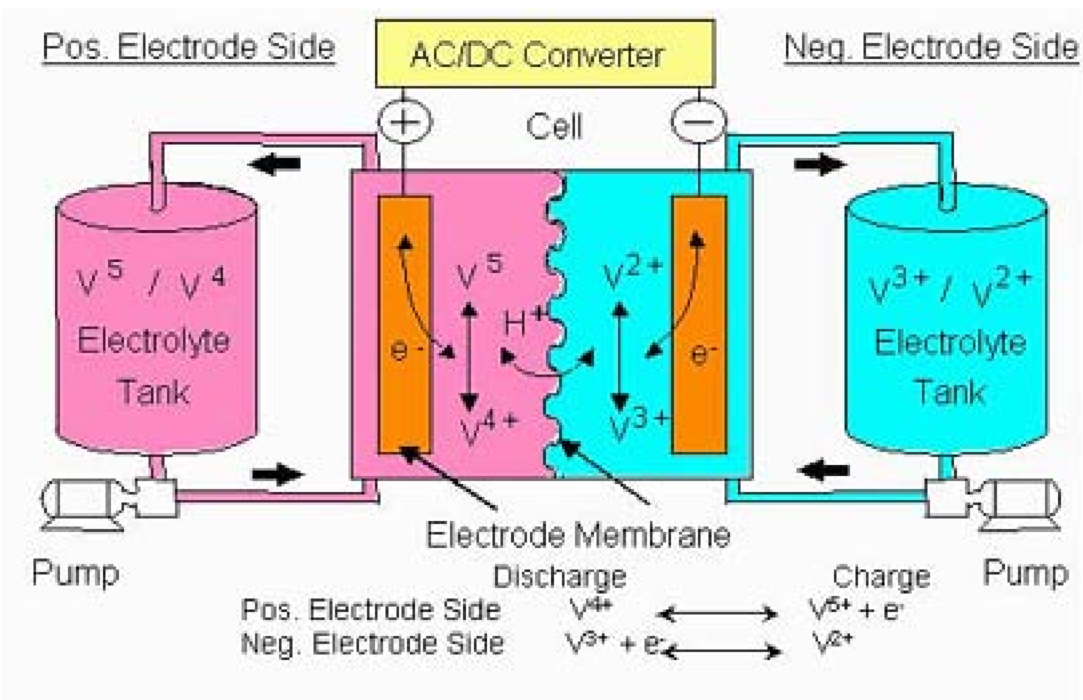

Figure A.4. Vanadium-redox Battery.

Another rechargeable "flow" battery is the Regenesys® system produced by Innogy, PLC in the UK. This system uses polysulfide as the active species. A block diagram for this battery is shown in Figure A.5. One interesting feature of this system is that the stack, or power section, is constructed more similarly to a reversible fuel cell stack than to a conventional battery. Hence, Innogy calls it a regenerative fuel cell.

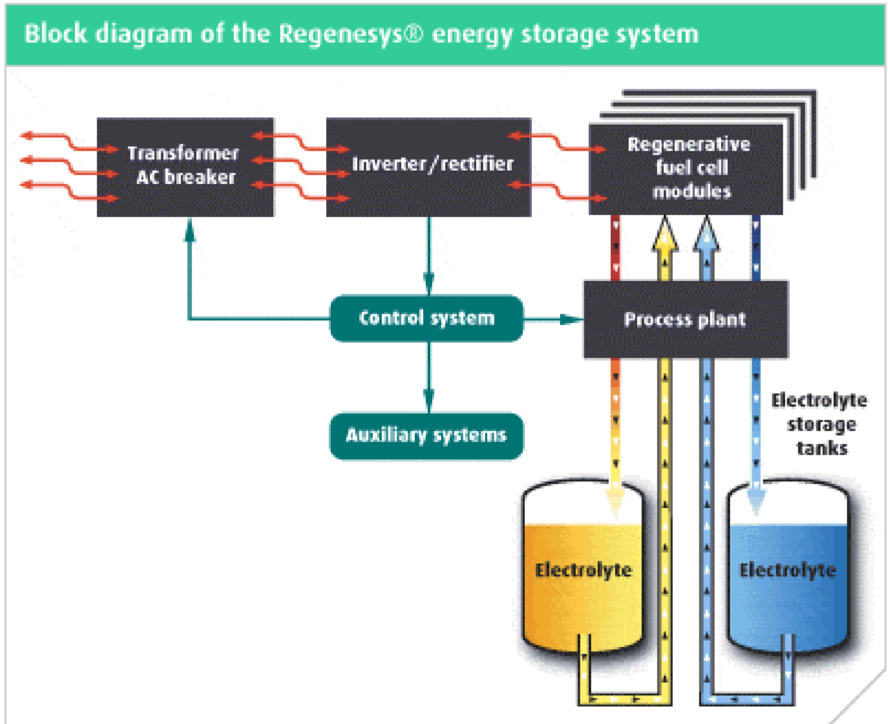

Figure A.5. Regenesys® System (Courtesy of Innogy, PLC).

A.3.4 Conventional (hydrocarbon) Fuel Cell

A conventional fuel cell power plant is typically fueled by natural gas. The natural gas is processed to generate hydrogen, discarding carbon dioxide. The power conversion stack combines the hydrogen with air to produce power and the byproduct water. Other hydrocarbon fuels can be used, such as propane, but natural gas, which is primarily methane, is one of the cleanest fuels. As long as gas is available, the fuel cell can operate continually.

Several types of fuel cells are commercially available in a range of sizes. Most commercial systems are based on a phosphoric acid electrolyte. Others use molten carbonate and solid oxide cells. The most recent development is the proton exchange membrane or polymer electrolyte membrane fuel cell (PEM). The PEM is gaining popularity because of its ambient temperature operation.

A commercial phosphoric acid fuel cell power plant, fueled by natural gas, is shown in Figure A.6.

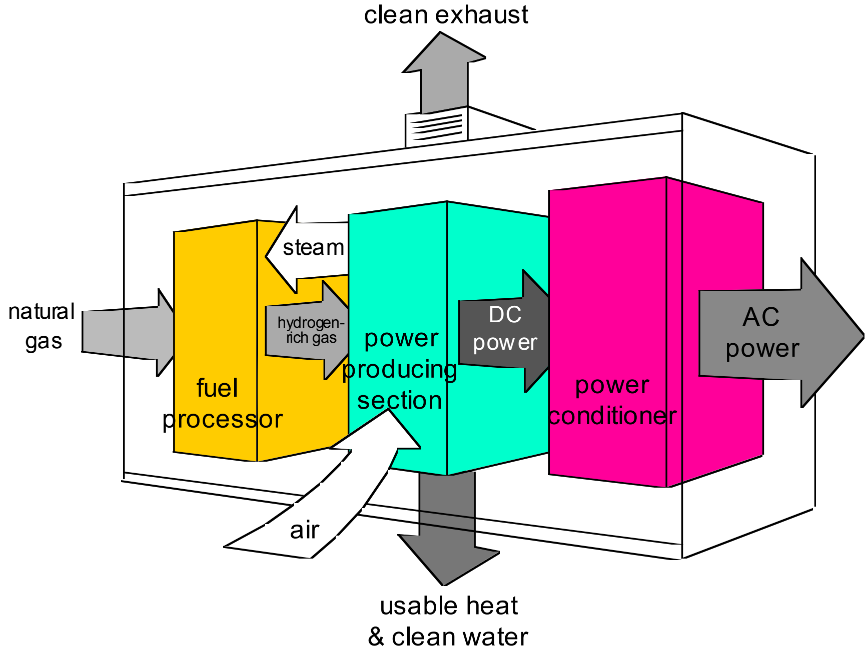

Figure A.6. Fuel Cell Power Plant (Courtesy of ONSI Division of International Fuel Cell).

A.3.5 Hydrogen Fuel Cell

The fundamental reaction in most fuel cells involves the migration of hydrogen ions through an electrolyte. The hydrogen can come from any number of fuels, as discussed above, or can be provided independently to the system. Hydrogen can be stored as a liquid (at cryogenic temperatures), as a gas (often compressed to reduce volume), or adsorbed on a metal or carbon solid. A proton exchange membrane fuel cell, fueled by hydrogen gas, is shown in Figure A.7.

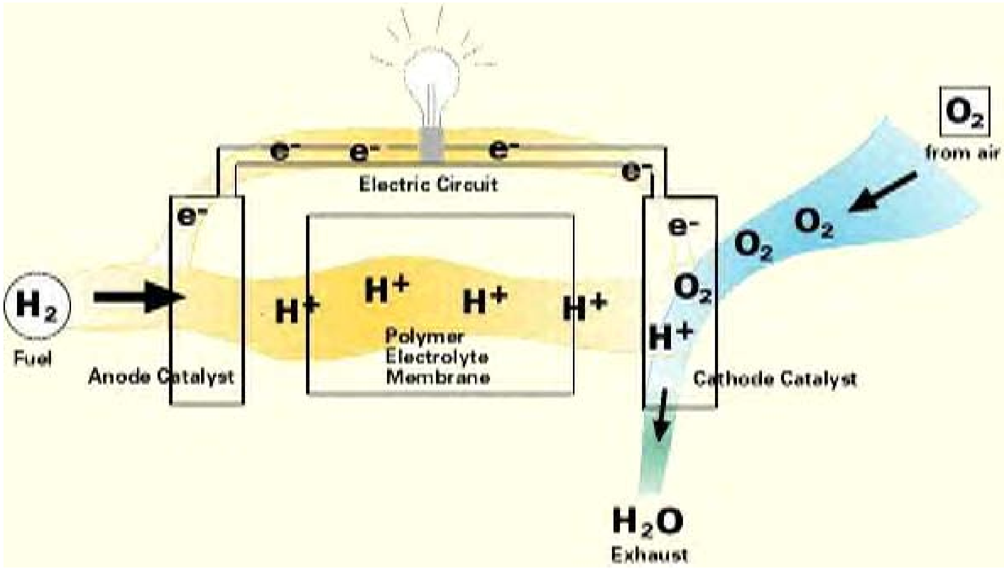

Figure A.7. Hydrogen-fueled Fuel Cell (Courtesy of DOE Hydrogen Information Web Site).

A.3.6 Reversible Fuel Cell

Some PEM fuel cells can be operated in the reverse direction. When electricity is applied, the water molecule will dissociate into hydrogen and oxygen. The hydrogen can be stored to be used later. The oxygen is typically discarded, as air is readily available in most applications. Such a system is a true rechargeable energy storage system, just like a rechargeable battery. Several developers are working on reversible fuel cells. They are not necessarily optimally efficient in either direction, but the overall system has advantages compared to using consumable resources. A reversible hydrogen fuel cell system is shown in Figure A.8a and A.8b.

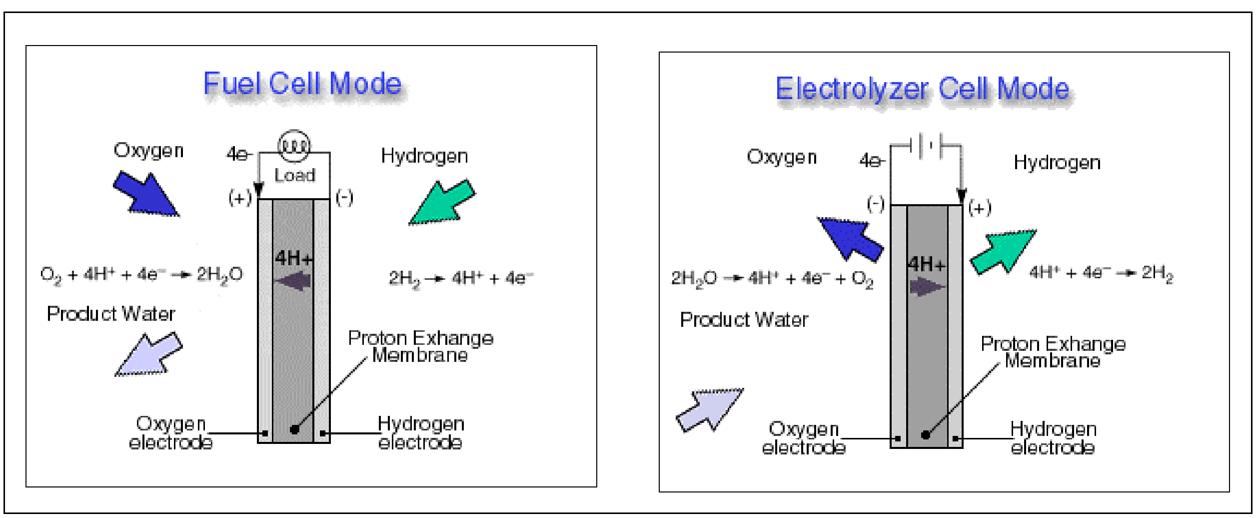

Figure A.8a. Fuel Cell mode of Reversible Fuel Cell. A.8b. Electrolyzer Mode. (Courtesy of *EcoSoul*).

A hydrogen system employing both a separate fuel cell and a separate electrolyzer (which incorporates a PCS and a rectifier, respectively) can also be considered as a rechargeable energy storage system, as shown in Figure A.9. In this case, although there are two independent units, each can be sized and optimized separately, with the opportunity to reduce overall system cost.

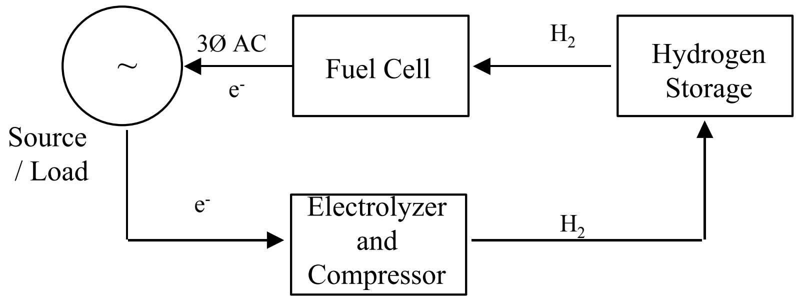

Figure A.9. Hydrogen Fuel Cell Energy Storage System with Separate Electrolyzer.

A.3.7 Millennium Cell

The Millennium Cell/Hydrogen-on-Demand™ system is neither a battery nor a fuel cell, but rather a hydrogen generator. Hydrogen is produced from $NaBH_4$ and is intended for use in a PEM fuel cell or possibly an internal combustion engine modified to run on hydrogen. This technology is included here because of the interest in novel approaches to providing clean energy. The Hydrogen-on-Demand™ system is shown in Figure A.10.

"Millennium Cell" is also developing a sodium borohydride disposable battery. The reaction is $BH_4 + 2\ O_2 \longrightarrow NaBO_2 + 2\ H_2O$.

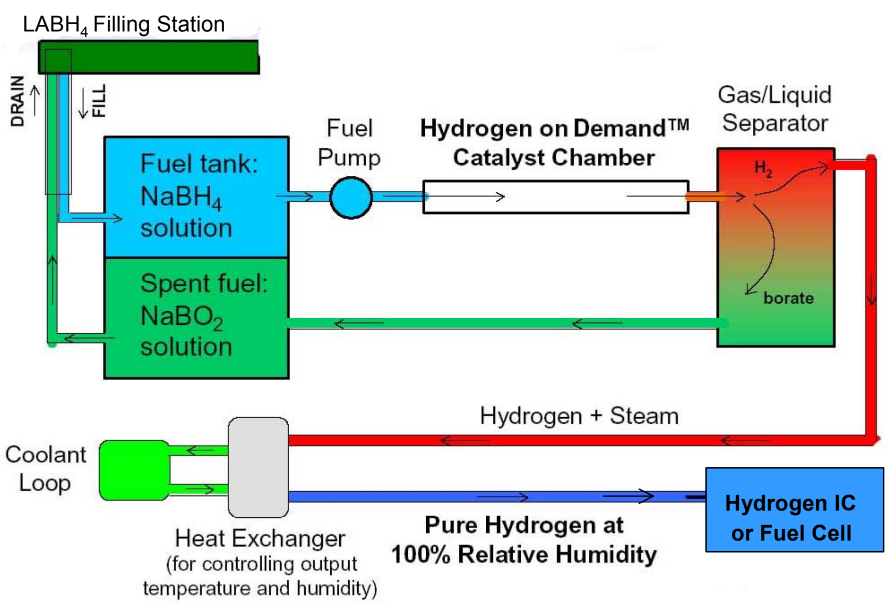

Figure A.10. Millennium Cell Hydrogen-on-Demand™ Flow Diagram.

The reaction is very energetic and the components are very lightweight. Millennium Cell is expecting good performance and long life from these batteries.

A.4 Applications of Batteries and Fuel Cells

A.4.1 Batteries

Typically, batteries are used for a very wide range of applications. The discharge time or storage capacity is determined by the "size" of the battery. The power level is determined by the system configuration. Commonly used for consumer products, batteries are also used in cars–both for starting and continuous use–and in industrial and electric utility applications. Most recently, batteries have been installed for utility peak shaving, for power quality/reliability applications, and for distributed energy resources. In general, when compared to fuel cells, batteries are best suited for shorter duration applications.

A.4.2 Fuel Cells

Conventional fuel cell systems are designed for continuous operation, as power plants for large customer loads, or for individual industrial or facility power. In normal applications, there is no time limit for the operation of the fuel cell that is fueled by natural gas or other hydrogen-containing fuel. The power level is determined by the configuration of the fuel cell stack.

A.4.3 Energy Storage

When a hydrogen fuel cell is used in an energy storage system, however, it is limited by the storage capability of the hydrogen storage medium. In this case, it is similar to a battery system. The ability to generate hydrogen, either by reversing operation of the fuel cell, or by adding an electrolyzer to the system, also determines the practical operating times of the fuel cell. In general, hydrogen storage is less expensive than battery energy storage. Fuel cell stacks are currently more expensive than battery cells. As a result, fuel cell energy storage systems are generally more attractive for longer duration applications - like load leveling - while battery energy storage systems are more attractive for shorter duration applications - like peak shaving. Figure A.11 shows this distinction on the basis of capital carrying charge.

A.5 Commercial Status

There are many manufacturers of both battery and fuel cell systems. Table A.1. outlines some manufacturers mentioned in this Appendix and others in the utility power industry.

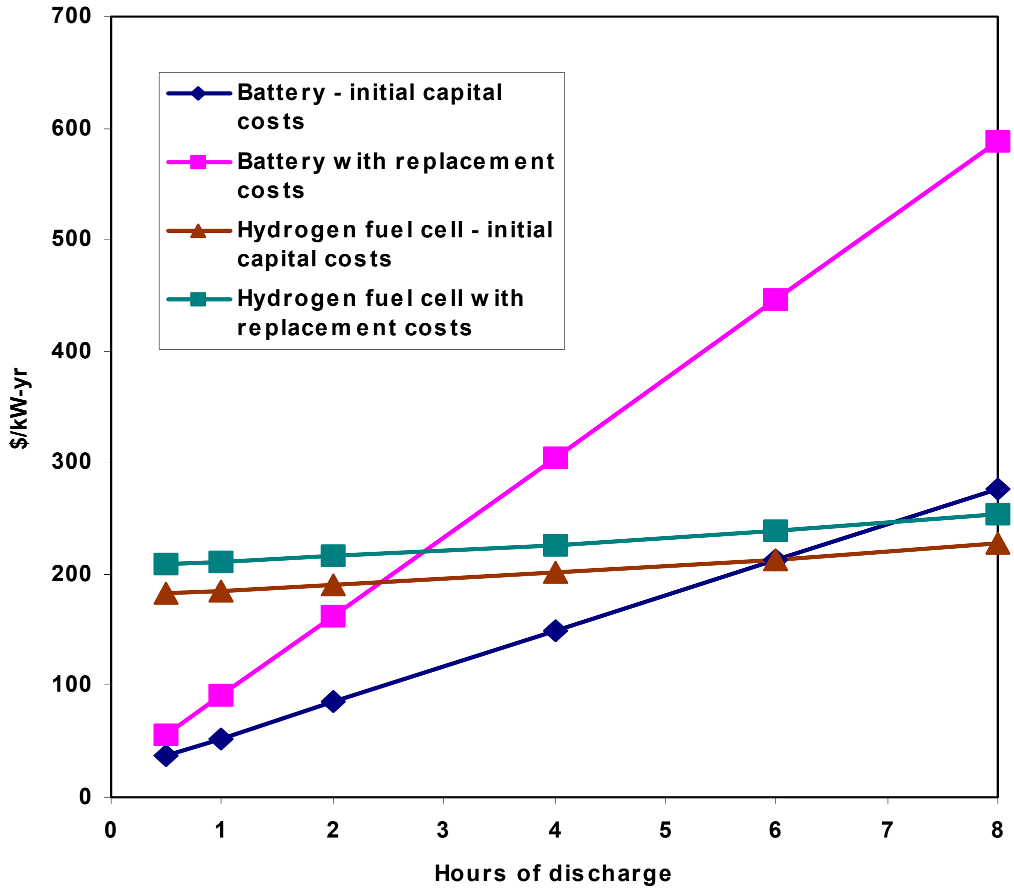

Figure A.11. Capital Carrying Costs of Batteries and Hydrogen Fuel Cell Energy Storage Systems in Load-Leveling Applications.

Table A.1. Partial List of manufacturers / Status of products

Product	Manufacturer	Location	Status of Product
Lead-acid battery energy storage systems	GNB/Exide	Lombard, IL	Commercial
	S&C / Delco	Chicago, IL	Commercial
Zinc/bromine flow battery	ZBB	Milwaukee, Wisconsin	Commercial
	Premium Power Corp. (PowerCell)	Boston, Massachusetts	Suspended operations
Vanadium-redox	Sumitomo Electric	Osaka, Japan	Prototypes available
	Vanteck (VRB)	Vancouver, Canada and Australia	In field test
Regenesys®	Innogy, PLC	Wiltshire, England	Prototypes available
Sodium borohydrate battery	Millennium Cell	Eatontown, NJ	In development
Phosphoric acid fuel cell	ONSI division of International Fuel Cells	Windsor, CT	Commercial
Molten carbonate fuel cell	Fuel Cell Energy	Danbury, CT	In demonstration
Solid oxide fuel cell	Siemens-Westinghouse	Pittsburgh, PA	In field test
PEM (hydrogen) fuel cell	Plug Power	Latham, NY	Commercial
	Ballard Power Systems	Vancouver, Canada	Prototypes available
	Avista Labs	Spokane, WA	Small units commercially available
Reversible fuel cell	Proton Energy Systems	Wallingford, CT	In development
	Technology Management, Inc.	Cleveland, OH	Research
Hydrogen-on-demand™	Millennium Cell	Eatontown, NJ	In development

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