Characteristics of Energy Storage Technologies for Short- and Long-Duration Applications

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Introduction

Applications of energy storage have a wide range of performance requirements, depending on the customer need. One important feature is storage time or discharge duration. A typical utility load-leveling application may require many hours of storage capacity, whereas a distributed generation / peaking unit may operate a maximum of an hour at a time. Energy storage is now commonly used to ensure power quality in facilities with extremely sensitive equipment. This application usually requires only seconds of carry-over during a voltage fluctuation.

In this study[2], applications and technologies have been evaluated to determine how storage charge / discharge time requirements can be matched by the storage capacities of various technologies. Comparisons have also been made on the basis of power ratings, which must also meet the need of the user. Another important characteristic is time response - how quickly must the energy storage system be able to respond, i.e., begin delivery of power to the user?

In addition to these performance characteristics, system capital costs have been evaluated for a variety of energy storage systems. The systems considered operate over a range of discharge times, characterized as short-term (<2 hrs) and long-term (2-8 hrs). Additional categories of very short-term (<1 min.) and very long-term (a day to weeks) were also considered. The technologies evaluated included:

- batteries (conventional and advanced),
- flywheels (low and high speed),
- supercapacitors,
- compressed air energy storage (CAES), and compressed air storage in tanks (CAS)
- superconducting magnetic energy storage (SMES),
- pumped hydro, and
- hydrogen (for use with fuel cells or combustion engines).

The study was based on known energy storage systems – some commercially available, and some in development.

In this paper, results of the capital cost assessment are presented. More details can be found in References [1,2]. In follow-on work, the charge / discharge efficiency of the system, the parasitic energy needs of the system, and the annual operating costs, are being evaluated so that life cycle costs for the various technologies can be compared. This adds another dimension to the cost assessment beyond just capital cost.

Applications

The applications and technologies analyzed in this study can be characterized by three different configurations. The most typical energy storage application is for load management. In this type of system, energy is discharged when need exceeds the normal load, i.e., for peak power. Peaking events can last from half an hour to as long as 8 hours. Distributed generation applications usually fall at the shorter end of this range. Bulk load-leveling applications tend toward the upper end. Load-leveling also implies the use of the storage unit to provide load during very low-load or off-peak periods. This is when the storage unit is recharged for its next discharge use. It is important to note that in load-leveling, both the discharge and charge uses provide benefits. Also, for load-leveling applications, it is generally assumed that the system is designed to charge (or provide load) at the same power level as it discharges. This means it can be recharged in roughly the same time as it can be discharged. The configuration for this application is shown schematically in Figure 1. The power

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conditioning system (PCS) serves as the interface between the energy storage unit and the grid. Technologies designed for this application include pumped hydro, CAES, batteries, SMES, and some flywheels.

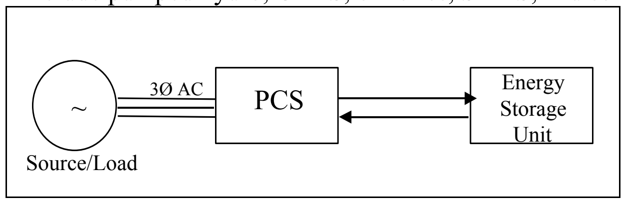

Figure 1. An energy storage system connected directly to the electric grid via a power conversion system

A second typical application of energy storage is for power quality or reliable power. This application can be suitable for customer end-use to protect a sensitive load, such as a computer or processing equipment, from voltage sags for momentary outages. It can also apply to high power transmission lines where protection from voltage or frequency disturbances is important. In either case, the role of the energy storage system is to briefly supply power, or voltage, or sometimes load to ride through the disturbance. In this case, the energy storage system appears somewhat detached from the normal bus until needed. In these applications, the charging cycle does not really provide a benefit. It is designed to minimize cost, which generally means a slow recharge. If frequent discharges are expected, the system is sized for all the discharge energy that might be needed in a single day. Figure 2 shows a power quality configuration. Technologies that are designed for this application included micro-SMES, batteries, supercapacitors, and flywheels.

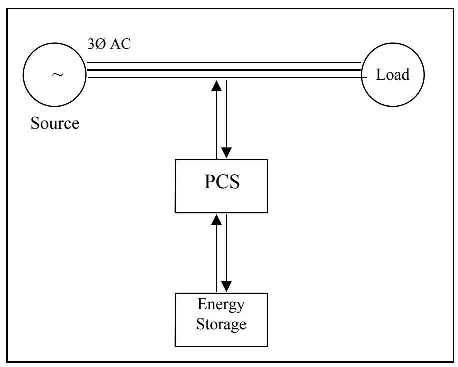

Figure 2. An energy storage system connected to a bus which feeds the load

The third configuration evaluated in this study is one that uses hydrogen as the source of stored energy. The hydrogen is used in a fuel cell or combustion engine to provide power. This system is included because it is a good candidate for distributed generation applications. To be considered an energy storage system, there must be a way to recharge the hydrogen storage. An elegant way would be to use a fuel cell in reverse, as an electrolyzer, to generate hydrogen from the water produced during discharge. And while there are research groups working to develop such a system, there are no reversible systems commercially available, and so this solution was not considered in this study. Instead, a hydrogen-based system would include a separate electrolyzer to recharge the hydrogen storage. Figure 3 shows an energy storage configuration based on hydrogen. The power unit (fuel cell or combustion engine) is sized for the peaking load. To minimize cost, the electrolyzer is rated at a power which can produced sufficient hydrogen to recharge the storage capacity over the remaining hours of the day. There are other types of fuel cells that can be used in distributed generation applications. These are typically fueled with natural gas and do not require hydrogen storage or recharging subsystems. They are not considered here because they cannot be called energy storage systems.

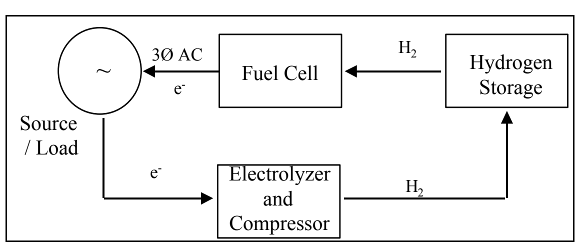

Figure 3. Hydrogen energy storage system showing the electrolyzer used to produce the stored hydrogen

Performance Fit Results

Technologies can be matched to applications in a variety of ways. Certainly cost can be a deciding factor. But the performance must also meet the application requirements. The most important characteristics are power, stored energy, and response time. If a technology cannot provide all of these characteristics, it is not suited to the application. Figure 4 shows numerous energy storage system products plotted by characteristics of power delivered and energy stored.[20] Overlayed on the chart are lines indicating discharge times: 1 sec, 1 min, 1 hr. The plot is logarithmic and covers a wide range of time scales. Some general application areas are indicated: e.g., power quality, load management, distributed resources.

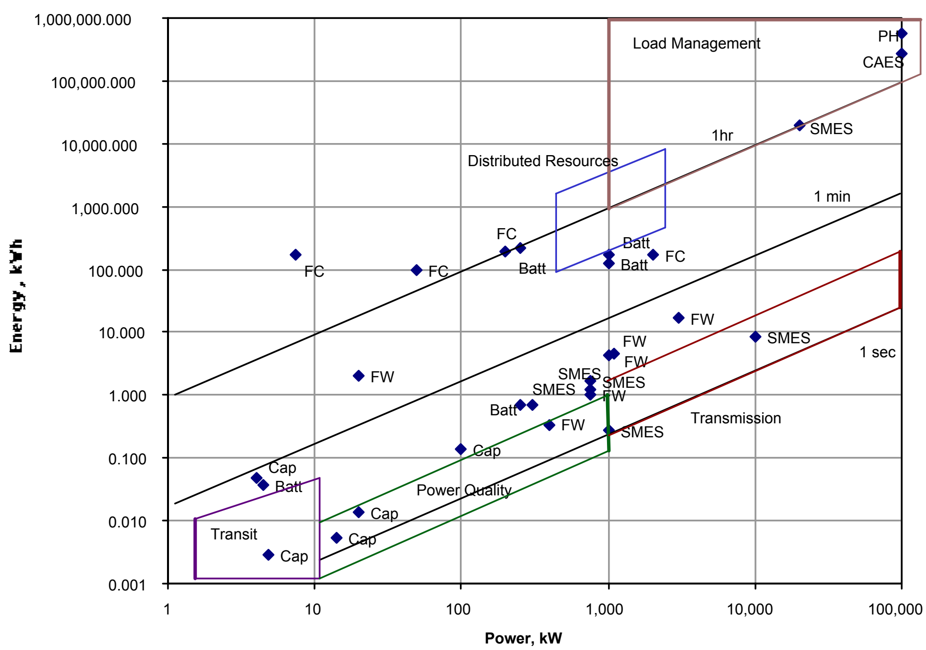

Figure 4. Power and Energy Characteristics of Energy Storage Products

Legend: FW=Flywheel, FC=Fuel Cell, Batt=Lead-Acid Battery, Cap=Supercapacitor, SMES=Superconducting Magnetic Energy Storage, PH=Pumped Hydro, CAES=Compressed Air Energy Storage.

Figure 5 indicates typical response times for the various technologies. Those with solid state power conversion interfaces can often respond at sub-cycle rates, assuming they are on "stand-by." Those with mechanical inertia, such as air or water turbines, require longer start-up or response time. Most fuel cell systems also require warm-up or flow time, but recent advances are making quick-response fuel cells available as well. [3]

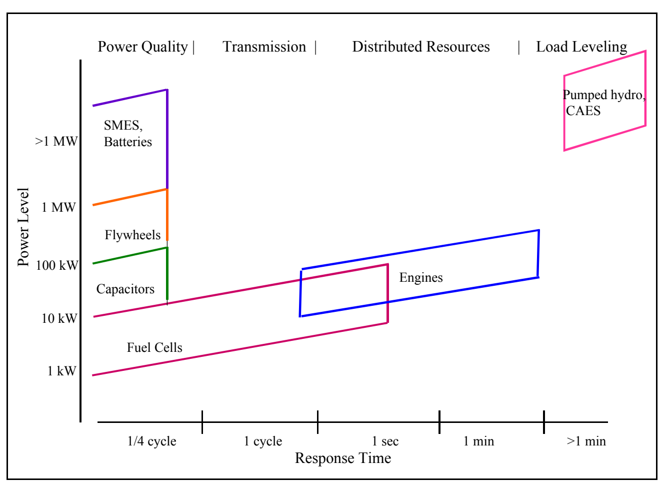

Figure 5. Response Characteristics of Energy Storage Systems (Fuel cells are hydrogen-fueled in stand-by mode.)

Capital Cost Analysis

One major objective of this study was to compare system capital costs for the various technologies in several representative applications. For those systems which consist of the energy storage unit and a single power conversion system that operates in both the discharge and charging modes, the system cost is the sum of the component costs plus Balance of Plant (BoP):

$$Cost_{total}\ (\$) = Cost_{pcs}\ (\$) + Cost_{storage}\ (\$) + Cost_{BoP}\ (\$) \tag{1}$$

For most systems, the cost of the PCS is proportional to the power level:

$$Cost_{pcs}\ (\$) = UnitCost_{pcs}\ (\$/kW) \times P\ (kW), \tag{2}$$

where P is the power rating.

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

$$Cost_{storage}\ (\$) = UnitCost_{storage}\ (\$/kWh) \times E\ (kWh), \tag{3}$$

where E is the stored energy capacity.

In the simplest case, E is equal to $P \times t$, where t is the discharge time. There are some exceptions and constraints to these simple equations. For one, the charge and discharge processes have some inefficiencies. For another, some systems cannot be fully discharged, and thus the storage capacity must be oversized. Yet another issue is that for some technologies, SMES in particular, the per-unit-energy cost is strongly dependent on the system size or stored energy. All of these factors have been taken into account in the cost analysis. Furthermore, hydrogen system costs are somewhat more complicated because the power and electrolyzer units are sized independently, based on the anticipated discharge cost. Cost assumptions are found in Table 1. Note that batteries and fuel cells have both "high" and "low" cost estimates. More details of the cost analysis can be found in Ref. [1 and 4].

Table 3. Energy Storage Technologies Costs and Efficiencies

	Energy related cost ($/kWh)	Power - related cost ($/kW)	Balance of Plant ($/kWh)	Electrolyzer ($/kW)	Compressor ($/scfm)	η, Discharge Efficiency
Lead-acid Batteries (low)	175	200	50			0.85
Lead-acid Batteries (high)	250	300	50			0.85
Power Quality Batteries	100	250	40			.85
Advanced Batteries	245	300	40			0.7
Micro-SMES	72,000	300	10,000			0.95
Mid-SMES (HTS projected)	2000	300	1500			0.95
SMES (HTS projected)	500	300	100			0.95
Flywheels (high-speed)	25,000	350	1000			0.93
Flywheels (low-speed)	300	280	80			0.9
Supercapacitors	82,000	300	10,000			0.95
Compressed Air Energy Storage (CAES)	3	425	50			0.79
Compressed Air storage in vessels (CAS)	50	517	50			0.7
Pumped Hydro	10	600	2			0.87
Hydrogen Fuel Cell / Gas Storage (low)	15	500	50	300	112.5	0.59
Hydrogen Fuel Cell / Gas Storage (high)	15	1500	50	600	112.5	0.59
Hydrogen engine /Gas Storage	15	350	40	300	112.5	0.44

Cost Results

Using the analytical approach described previously, the capital costs of the various technologies have been calculated for a variety of applications. The results are shown as cost in dollars-per-kW in Figures 6-9. Strictly speaking, this is not the best way to show results for some cases because of components that are not linear with power level. However, the comparisons are consistent at each point.

Figure 6 shows the capital cost results for end-use power quality systems. These are technologies operating up to several MW for very short time (0 - 20 sec). In this range, the comparison is highly dependent on the discharge time (or stored energy). Thus it is important to determine carefully how long a discharge is really required. Oversizing can be costly.

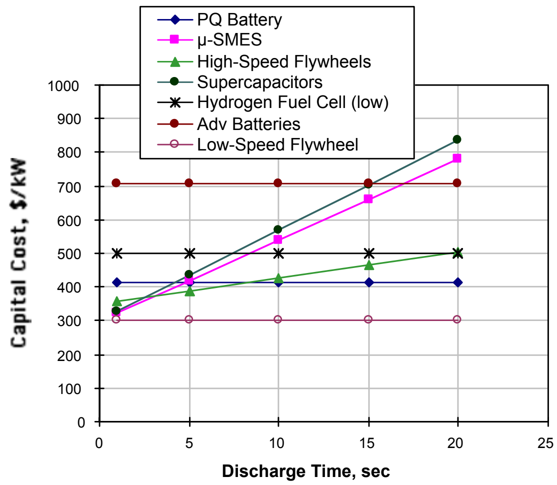

Figure 6. Capital Cost of End-Use Power Quality Systems (very short time: 0 - 20 sec, 1 - 4 MW)

Figure 7 shows the results for distributed generation applications with power levels up to 2 MW and discharge time up to two hours. This technology is also suitable for matching irregular or intermittent renewable resources with steady or peaking loads. The "knee" in the battery curves occurs because the shortest full discharge time for most batteries is actually an hour. It is not possible to realize savings by discharging less energy from the battery. Figure 8 includes the cost of a hydrogen-fueled combustion engine for distributed generation applications in the same size range. It is included as yet another near-term option for clean, inexpensive peaking power.

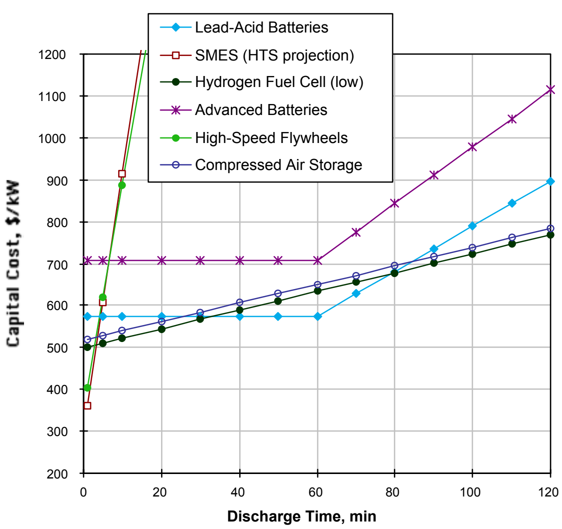

Figure 7. Capital Cost for Distributed Utility Applications and Renewables Matching (short time: 10 min. to 2 hours, <2 MW)

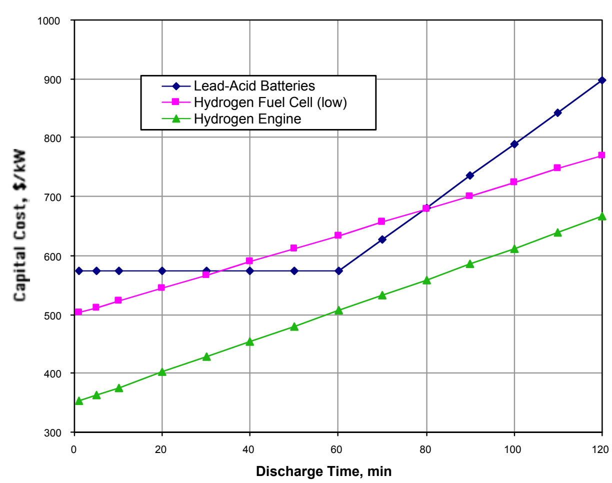

Figure 8. Comparison of Hydrogen-Fueled Combustion Engine (at today's prices) with Fuel Cell and Batteries for Distributed Utility applications.

Finally, Figure 9 shows the results for load management or load-leveling applications. These are the large scale, central station applications. The least costly technologies are pumped hydro and CAES because these use relatively inexpensive "natural" storage. However, availability of sites is an issue. The next least expensive systems are those using manufactured storage reservoirs - air tanks and hydrogen tanks. Those based on the more sophisticated electrochemical (batteries) and electromagnetic (SMES) storage are more expensive.

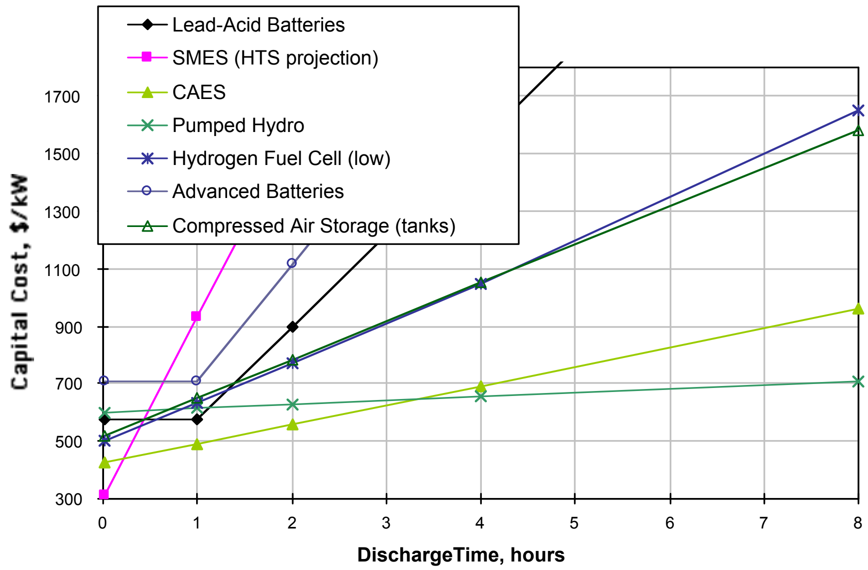

Figure 9. Capital Cost of Load Management Systems (long duration: 1 - 8 hrs, >10MW)

Conclusions

Some conclusions from this study, based on performance and capital cost, include:

- Flywheels are a good match for a range of short-term applications, up to a size of several MW.
- Batteries currently have the broadest overall range of applications.
- Fuel cells should be applicable and cost effective in a very broad range of applications in the future.
- Hydrogen-fueled combustion engines are a currently available technology for short-term applications including distributed utility applications, renewables matching, and spinning reserve.
- CAES and pumped hydro are best for load management when geology is available and response time in the order of minutes is acceptable. In the U.S. most suitable pumped hydro sites are already in use.
- SMES is a niche technology for power quality and especially high power distribution or transmission networks. Projected costs for bulk storage, however, show it to be expensive.

Follow-on work is being performed to update the cost and performance data for these technologies, and to provide an additional comparison on the basis of life cycle cost.

References

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