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Characteristics and Technologies for Long-vs. Short-Term Energy Storage

A Study by the DOE Energy Storage Systems Program

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Abstract

This report describes the results of a study on stationary energy storage technologies for a range of applications that were categorized according to storage duration (discharge time): long or short. The study was funded by the U.S. Department of Energy through the Energy Storage Systems Program. A wide variety of storage technologies were analyzed according to performance capabilities, cost projects, and readiness to serve these many applications, and the advantages and disadvantages of each are presented.

Acknowledgment

The author and Sandia National Laboratories wish to acknowledge the U.S. Department of Energy and specifically the Energy Storage Systems Program for support of this project.

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Acronyms and Abbreviations

APS	advanced pumped storage
CAES	compressed air energy storage
CAS	compressed air storage
HTS	high temperature superconductivity
PCS	power conversion system
SMES	superconducting magnetic energy storage
VAR	volt amp reactive

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Characteristics and Technologies for Long- vs. Short-Term Energy Storage – Final Report

Executive Summary

Applications of energy storage have a wide range of performance requirements. One important feature is storage time or discharge duration. In this study, applications and technologies have been evaluated to determine how storage time requirements match technology characteristics. Comparisons have also been made on the basis of capital cost for various energy storage systems operating over a range of discharge times, categorized as short-term (< 2 hrs) and long-term (2-8 hrs). Special categories of very short term (< 1 min) and very long term (a day to weeks) were also considered. The technologies evaluated included: batteries (lead-acid and advanced), flywheels (low and high speed), supercapacitors, superconducting magnetic energy storage, compressed air energy storage, pumped hydro, and hydrogen.

Some conclusions from this study 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.
- 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.

1. Introduction

1.1 Background

The United States Department of Energy, through the Energy Storage Systems Program at Sandia National Laboratories is working with the utility industry and the manufacturing sector to develop energy storage systems for applications of interest to industry.

There are three main thrust areas:

- reliability,
- renewables, and
- productivity.

Among these areas are specific applications of energy storage, with varying requirements for power level and storage capacity. Numerous types of storage systems are available, or becoming available, to meet these needs. It is important to identify a suitable match between requirements and the performance of various types of technologies. The overall goal of this project is to address this match by examining both performance characteristics and cost.

1.2 Objectives

The specific objective of this study is to characterize the stationary applications and technologies of short and long-term storage. Storage lasting seconds to several hours is considered short-term, while storage of greater than a few hours is considered long-term. The applications requiring short-term storage and long-term storage are described. The characteristics of storage types (including batteries, flywheels, supercapacitors, superconducting magnetic energy storage, compressed air energy storage, pumped hydroelectric storage, and hydrogen storage) are described. The degree of matching between the applications' storage times and the storage technologies' characteristics is then presented.

1.3 Report format

Section 2 of this report describes briefly the applications considered and characterizes them by performance requirements, including power, energy, and response time. Section 3 briefly describes the storage technologies considered and their characteristics. Section 3 also presents the cost analysis for the various types of technologies in representative applications. Most are costed by summing the power-related components, the energy-related components, and the balance of plant. Section 4 presents the results of the analysis and matching exercise. Finally, Section 5 presents conclusions and recommendations.

2. Applications

Sandia has been pursuing three thrust areas in the research and development of energy storage for the utility sector. These are reliability, renewables, and productivity[1]. Energy storage can address and benefit these thrusts in a variety of ways. Applications in these areas can be more specifically categorized by the functions which are recognized by utilities and their customers. These applications include:

- Load management

  Load management includes the traditional load-leveling application of energy storage, in which energy is stored during off-peak hours (typically at night) and then discharged during peak hours. This not only saves money on the basis of the difference between peak and off-peak rates, but also provides a more uniform load factor for the generation, transmission and distribution systems. Other types of load management are ramping and load-following.

- Remote power

  In some remote locations it is not practical to bring power to a site from an established utility grid. Power may be generated from diesel or gas generators, fuel cells or renewable sources. For local load management, it may be useful to include energy storage to minimize the generation capacity.

- Spinning reserve

  Most electric utilities operate with a requirement for spinning reserve. This generation is ready, or in "hot stand-by", should an electric generating unit somewhere on the system fail. The available reserve power is determined by the configuration and mix of unit capacities on the system. Typically, the reserve power must equal the power output of the largest generating unit in operation.

- Renewables matching

  Renewable energy sources, such as wind and solar, are desirable because they are non-polluting and in plentiful supply. By their very nature, however, they are intermittent; often the profile of energy generation does not coincide with the demand cycle. Energy storage can be used to match the output of renewable sources with any load profile.

- Transmission enhancement

  Energy storage can improve transmission capacity by providing line stability, voltage regulation, frequency regulation, and VAR or phase angle control. Specialized power electronic equipment must be located in suitable locations along transmission lines. The amount of energy injected is often small, but at relatively high power.

- Distributed resources

  Distribution systems in many growing urban and suburban areas are subject to dramatic day-time peaking. It is often more cost-effective to add distributed generation resources in critical locations than to upgrade distribution wires. Energy storage can be ideal for this application because recharging can take place during off-peak periods.

- Power quality

  Utility power sometimes suffers disturbances such as momentary voltage sags or even outages. These events, along with harmonic distortions, and other imperfections can affect sensitive processing equipment that needs extremely clean power to operate properly. Energy storage systems are being successfully installed to provide reliable and high quality power to sensitive loads. Sometimes the systems are coupled directly to the critical equipment, and sometimes to the bus feeding a facility or even on a feeder line.

- End-use

  Although the primary end-use application for energy storage is for power quality, there are other customer uses. These include local peak shaving (to avoid time-of-day charges) and process enhancements (e.g., in pulsed power processes, or other specialized industrial applications).

- Transit

  Many electric transit systems could benefit from energy storage because of the highly variable load they create during braking and start-up. Many types of energy storage can provide regenerative braking, accepting energy from the propulsion system during deceleration; and then providing a boost during acceleration.

More discussion of these applications can be found in Ref [2-4]. These many applications can also be characterized by their technical requirements, i.e., power level, energy storage capacity, and response time. The energy storage capacity is specifically determined by the time duration required for delivery or discharge. Applications tend to fall into time categories of very short, short, long, and very long. Table 1 lists these applications and their range of characteristics.

3. Energy Storage Technologies and Systems

3.1 Technology Descriptions

For this study, a number of different energy storage technologies were considered. These include: batteries (lead-acid and advanced), flywheels (low speed and high speed), supercapacitors, compressed air energy storage, superconducting magnetic energy storage, pumped hydro electric storage, and hydrogen storage. These technologies are described very briefly below. More information can be found in References [5 – 6].

Batteries (Lead-Acid and Advanced)

Batteries are a well known type of energy storage. Electric batteries are devices which store electric energy in electrochemical form. Electrode plates, typically consisting of chemically reactive materials, are placed in an electrolyte which facilitates transfer of ions within the battery. The negative electrode, or anode, "gives up" electrons during discharge via the oxidation part of the oxidation-reduction electrochemical process. Those electrons flow through the electric load connected to the battery, giving up energy. Electrons are then transported to the positive electrode, or cathode, for electrochemical reduction. The process is reversed during charging. Battery systems consist of cells, which have a characteristic operating voltage and maximum current capability, configured in various series/parallel arrays to create the desired voltage and current. Batteries store and deliver direct current (dc) electricity. Thus, power conversion equipment – primarily an inverter – is required to connect a battery to the alternating current (ac) electric grid.

The most mature battery systems are based on lead-acid technology. Most of the analysis in this report is performed for lead-acid batteries. In this study, costs for lead-acid batteries have been further divided into "high" and "low", which represent current and projected future costs, respectively.

Other advanced technologies have been developed which may have advantages over lead-acid, in terms of performance, handling characteristics, cost, or life time. Two types considered in this study are zinc/bromine (Zn/Br) and sodium/sulfur (Na/S). [7,8]

Table 1. Energy Storage Applications and Their Characteristics

APPLICATION	Power	Storage Time	Energy	Response time
Very short duration			kWh	
End-use ride through, power quality, motor starting	≤ 1 MW	secs	~0.2	< 1/4 cycle
Transit	< 1 MW	secs	~0.2	< 1 cycle
T&D stabilization	up to 100's MW	secs	20 - 50	< 1/4 cycle
Short duration			kWh	
Distributed generation (peaking)	0.5 to 5 MW	~1 hr	5000 - 50,000	< 1 min
End-use peak shaving (to avoid demand charges)	< 1 MW	~1 hr	1000	< 1 min
Spinning reserve – rapid response within 3 sec to avoid automatic shift	1 - 100 MW	< 30 min	5000 - 500,000	< 3 sec
Spinning reserve – conventional (respond within 10 min)	"	≤ 30 min	"	< 10 min
Telecommunications back-up	1-2 kW	~2 hrs	2 - 4	< 1 cycle
Renewable matching (intermittent)	up to 10 MW	min- 1 hr	10 - 10,000	< 1 cycle
Uninterruptible Power Supply	up to ~2 MW	~2 hrs	100 - 4000	secs
Long duration			MWh	
Generation, load leveling	100's MW	6-10 hrs	100 - 1000	mins
Ramping, load following	100's MW	several hrs	100 - 1000	< cycle
Very long duration			MWh	
Emergency back-up	1 MW	24 hrs	24	sec - mins
Seasonal storage	50-300 MW	weeks	10,000 - 100,000	mins
Renewables back-up	100 kW -1 MW	7 days	20 - 200	sec - mins

Flywheels (Low-Speed and High-Speed)

Flywheels store kinetic energy in a rotating mass. The amount of stored energy is dependent on the speed, the mass, and the configuration of the flywheel. They have been used as short-term energy storage devices for propulsion applications such as engines or large road vehicles. In these applications, a flywheel smoothes the power load during deceleration by dynamic braking and then provides a boost during acceleration. The same conversion process – from kinetic energy to AC electric power – is used in stationary applications of energy storage, especially for power quality or power back-up. Electrical energy is typically transmitted into and out of the flywheel system by a variable frequency motor/generator. Variable frequency capability is necessary because the rotational speed (frequency) of the flywheel will change as energy is charged or discharged from the device.

Flywheel energy storage systems available today are usually categorized as either low-speed or high-speed. High-speed wheels are made of high strength, low-density composite materials; these systems are considerably more compact than those employing lower-speed metallic wheels. However, the low-speed systems are still considerably less expensive (on a per-kWh basis). Both types are considered in this study, as both are currently being successfully applied to a variety of stationary applications.

Supercapacitors

Energy is stored in conventional capacitors in the electric charge between two conducting plates. The plates are separated by an insulating material known as dielectric. The capacitor is charged when a voltage differential is applied across the plates. The factors that determine the capacitance are the size of the plates, the separation of the plates and the type of material used for the dielectric. Energy is discharged by reversing the voltage direction.

The term "supercapacitor" reflects orders of magnitude of improvement in the energy density of DC capacitors through state-of-the-art selection and processing of electrode materials. They differ from common dielectric capacitors, because they store energy in a polarized liquid layer at the interface between a conducting ionic electrolyte and a conducting electrode. Because the capacitance is proportional to the surface area of the electrode, surface area enhancements are provided by using highly porous material. A wide variety of electrolytic solutions and surface treatments are currently being advanced. Many of these products are targeting electric vehicle applications, but are becoming available for higher power stationary applications. Cycle life for supercapacitors is also many times that of conventional capacitors.

Compressed Air Energy Storage (CAES)

CAES systems store energy by compressing air within an air reservoir using a compressor powered by off-peak/low cost electric energy. During charging, the plant's generator operates in reverse – as a motor – to send compressed air into the reservoir. When the plant discharges, it uses the compressed air to operate the combustion turbine generator. Natural gas is burned during plant discharge, in the same fashion as a conventional turbine plant. However, during discharge, the combustion turbine in a CAES plant uses all of its mechanical energy to generate electricity; thus the system is more efficient.

Compressed air can be stored in several different types of reservoirs: in naturally occurring aquifers (similar to conventional natural gas storage), in solution-mined salt caverns, or in constructed rock caverns. Aquifer storage is by far the least expensive and occurs in the most locations. Both aquifer and salt cavern storage systems are currently being operated at Huntorf, Germany, and at the McIntosh plant for the Alabama Electric Co-op, respectively. CAES is an attractive energy storage technology for large, bulk storage.

Another approach to compressed air storage has been studied. In this variation, referred to in this report as CAS, fabricated high-pressure tanks would be used as the reservoir. Because of the expense of such tanks, only several hours worth of storage has been proposed for this concept. [9, 10]

Superconducting Magnetic Energy Storage (SMES)

In SMES, energy is stored in the magnetic field produced by current circulating through a superconducting coil. The system is efficient because there are no resistive losses in the superconducting coil and losses in the solid state power conditioning are minimal. Like a battery, a SMES provides rapid response for either charge or discharge. Unlike a battery, the energy available is independent of the discharge rate. The interaction of the circulating current with the magnetic field produces large forces on the conductor. In a small magnet, these forces are easily carried by the conductor itself. In a large magnet, a support structure must be provided either within the coil windings or external to the coil to carry these loads.

Today's SMES units use conventional metallic superconductor material (Nb-Ti or Nb_3Sn) cooled by liquid helium for the coil windings. High temperature ceramic superconductors (HTS) cooled by liquid nitrogen are now being used in the power leads that connect the coil to the ambient temperature power conditioning system. Complete coil and lead designs based on HTS materials are in development because the refrigeration requirement is significantly reduced. [11, 12]

In this study, SMES systems are identified in three sizes, as: micro SMES (≤ 4 MJ), mid-SMES (up to 20 MWh), and SMES (up to 5000 MWh). Each size category differs in both design and cost from the others because of significant non-linearities in stored energy scaling over orders of magnitude.

Pumped Hydro Electric Storage

In pumped storage, a body of water at a relatively high elevation represents potential or "stored" energy. Electrical energy is produced by releasing the water from this reservoir, causing it to flow through hydroturbines and into a lower reservoir. The water is pumped back up to recharge the upper reservoir. Generation and pumping can be accomplished either by single-unit, reversible pump-turbines, or by separate pumps and turbines. Mode changes between pumping and generating can occur within a period of minutes, and up to 40+ times daily. Pumped storage facilities have operated in the United Sates since the late 1920s. Typically, upper and lower reservoirs have been constructed by dams. Within the last 10 years, advanced pumped storage (APS) technology has been developed to improve speed, reliability and efficiency. These plants are designed hydraulically and mechanically for ultrafast loading and ramping, allowing frequent and rapid (<15 sec) changes among the pumping, generating and stand-by spinning modes.

Hydrogen Storage

Hydrogen is not a primary energy source. Like electricity, it is an energy carrier between various sources and end uses. When used for energy storage, hydrogen is a fuel, storing energy in its chemical potential. Power is generated from hydrogen either by conversion in a fuel cell, or by combustion in an internal combustion or turbine engine. In this report, a hydrogen fuel cell system at both "high" and "low" cost projections is compared with all the other energy storage technologies. The hydrogen-fueled combustion engine is compared only with the fuel cell. Hydrogen can be stored in many configurations: as compressed gas in tanks, in underground reservoirs, or in tiny microspheres; as a (cryogenic) liquid; in hydride compounds; or in other chemical forms. The various storage types have different characteristics, some of the most important ones being energy density and cost. For purposes of this report, the primary storage form considered is as compressed gas in high pressure tanks, although hydride storage should eventually be comparable in cost. [13] Only for very long duration applications (requiring large storage volume) is underground storage considered.

3.2 Characterization

The various technologies are differentiated by their physical layout, chemical composition, and energy density. They also differ in their voltage and current output characteristics, such that the power conversion interface may differ for each technology and each will have unique time-varying output that must be matched. Other operational features, such as efficiency and size also vary for the different technologies. In this sudy, the various technologies were compared by the characteristics listed in Table 2. For all technologies, data for most of these items are included in the technology data sheets in the Appendix.

Table 2. Energy Storage System Characteristics

Capital cost
Balance of Plant
Energy-related
Power-related
Operating features
Efficiency
O&M costs
Cycle or shelf life
Other technology-specific costs
Parasitics
Replacement
Size
Siting issues
Environmental
Safety
Other features

3.3 System Diagrams

For most utility applications of energy storage, the system consists of the storage unit plus power conversion unit that interfaces the storage unit to the utility grid or user load. When energy is needed, it is discharged from the storage unit through the power conversion unit. The storage device is most typically recharged by supplying energy from the utility system at a later time. The purpose of the power conversion system is to match the voltage, current and power characteristics of the storage unit output with those of the load.

To illustrate a conventional energy storage system, a diagram is presented in Figure 1. In this configuration, the storage unit is interfaced to the grid through a PCS which operates in both the discharging and charging modes. A typical application of a system connected in this way would be for load leveling or peak shaving.

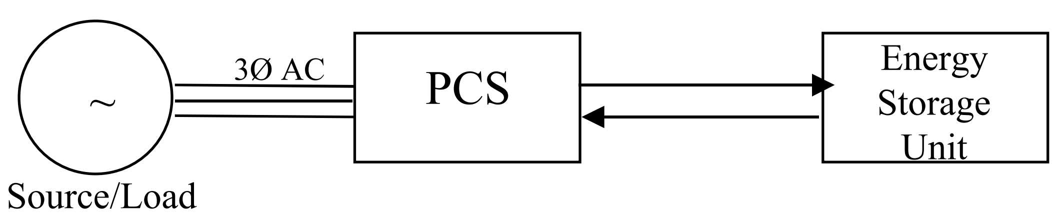

Figure 1. An energy storage system connected directly to the electric grid via a power conversion system.

In an end-use application, the energy storage system may be connected to the bus which 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. A typical arrangement is shown in Figure 2.

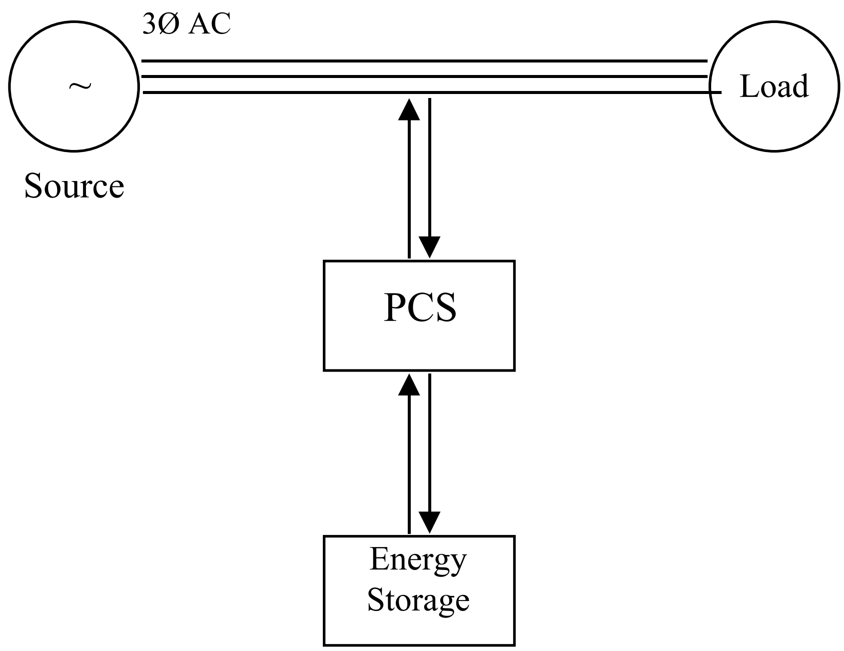

Figure 2. An energy storage system connected to a bus which feeds the load.

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 provides the hydrogen, while a fuel cell generates 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.

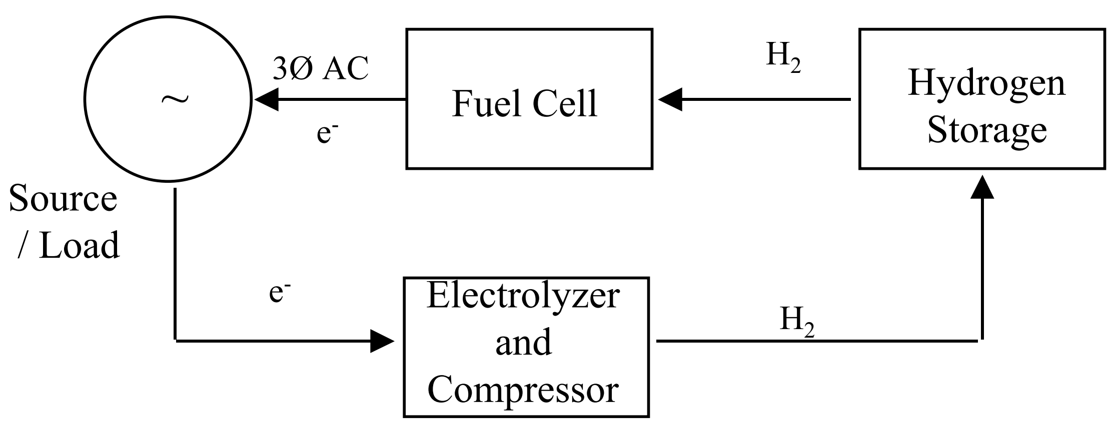

Figure 3. Hydrogen energy storage system showing the electrolyzer used to produce the stored hydrogen.

3.4 Cost Analysis

One major objective of this study was to compare system capital costs for the various technologies in several representative applications. This analysis follows from Ref [14]. 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):

$$Cost_{total}\ (\$) = Cost_{pcs}\ (\$) + Cost_{storage}\ (\$) + Cost_{Bop}\ (\$) \quad (1)$$

Hydrogen system costs are developed somewhat differently, as described later in this section.

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

$$Cost_{pcs}\ (\$) = UnitCost_{pcs}\ (\$/kW) \cdot P\ (kW), \quad (2)$$

where P is the power rating.

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

$$Cost_{storage}\ (\$) = UnitCost_{storage}\ (\$/kWh) \cdot E\ (kWh), \quad (3)$$

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. To begin with, all systems have some inefficiency. To account for this, Eq. 3 is modified as follows:

$$Cost_{storage}\ (\$) = UnitCost_{storage}\ (\$/kWh) \cdot (E\ (kWh)/\eta_{dis}) \quad (4)$$

where η_{dis} is the discharge efficiency.

In addition, many storage units are not discharged completely in operation because of voltage or mechanical considerations. In these cases, the storage 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 $E^{2/3}$. Thus, for this study, the unit costs for SMES are a function of E. [15]

Finally, for lead-acid batteries, the unit energy costs do not hold for short discharge times [16], 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 one-hour batteries. For the power quality application very inexpensive batteries were assumed ($100/kWh).

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. These are listed in the Appendix for the various technologies.

As indicated previously in Figure 3, a hydrogen-based energy storage system must include a separate "charging" component - the electrolyzer. A compressor is also required if the stored hydrogen is pressurized. To cost these additional items, their rating must be determined by the time available for charging. An important point is that the electrolyzer and compressor will operate during the time that the fuel cell is NOT operating, and thus the rating of these devices can be very small compared to the power rating at discharge. This is shown schematically in Figure 4.

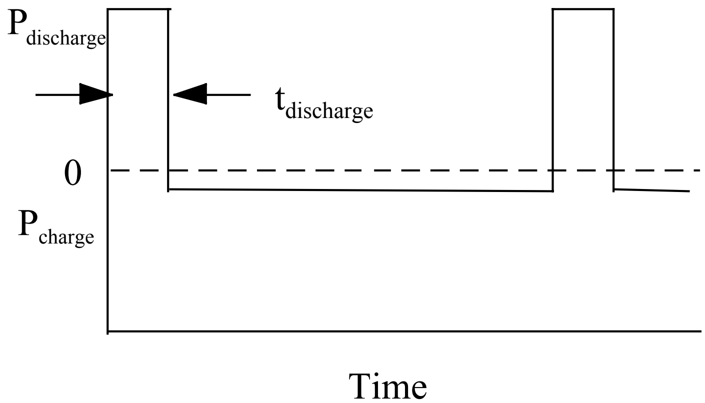

Figure 4. Schematic diagram of discharging and charging time for a hydrogen energy storage system.

A typical case might have a distributed utility unit discharging for a time, t_d, of 1 hour each day at power level $P_{discharge}$. The electrolyzer can recharge over the remaining t_{ch} = 24 hr - t_d(hr) = 23 hours and be rated at:

$$P_{charge} = \frac{P_{discharge} \bullet t_d}{t_{ch}}, \qquad (5)$$

or 1/23 the power level of the fuel cell.

In general, the charging time:

t_{ch} (hr) = 24 hr -t_d (hr)
t_{ch} (min) = (24 hr · 60 min/hr) - t_d (min)
t_{ch} (sec) = (24 hr · 3600 sec/hr) - t_d (sec)

This approach was used in calculating hydrogen system costs throughout this study. (This algorithm is modified if a duty cycle greater than once per day is anticipated.)

For pressurized storage, the compressor is sized to refill the storage over the same extended period. The compressor is sized based on hydrogen flow rate in standard cubic feet per minute. Cost data from [17] were used. Thus the total system cost for a hydrogen energy storage system is given as:

$$Cost_{H2total}(\$) = UnitCost_{gen}(\$/kW) \times P_{discharge}(kW) + UnitCost_{storage}(\$/kWh) \times \frac{E(kWh)}{\eta_{H2dis}} + UnitCost_{electrolyzer}(\$/kW) \times \frac{P_{discharge}(kW) \times t_d}{(t_{ch}) \times \eta_{H2dis}} + UnitCost_{comp}(\$/scfm) \times \frac{E(scfH_2)}{t_{ch}(\min) \times \eta_{H2dis}} \qquad (6)$$

where:

$UnitCost_{gen}$ = cost of hydrogen fuel cell, (\$/kW)

$UnitCost_{storage}$ = cost of hydrogen storage (cylinder or hydride), (\$/kWh)

$UnitCost_{electrolyzer}$ = cost of advanced electrolyzer (\$/kW)

$UnitCost_{comp}$ = cost of compressor for pressure required (\$/scfm)

$E(scfH_2) = E(kWh) \cdot 3600\ kJ/kWh \cdot 0.002722\ scfH_2/kJ$

η_{H2dis} = discharge efficiency

η_{H2dis} is the discharging or generating efficiency of the hydrogen system. This determines the sizing of the hydrogen reservoir to provide sufficient delivered energy. η_{H2dis} for a fuel cell system was assumed to be 0.59 [18] and for a combustion engine 0.44 [19].

The costs and efficiencies used in this study are listed in Table 3. Most of these were developed through discussions with vendors while others are found in recent literature. These values represent the latest available data and projections. Table 4 indicates the relative maturity of the technologies and certainty in the cost assumptions. (See the Appendix for sources.)

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 (medium)	225	250	50			0.85
Lead-acid Batteries (high)	250	300	50			0.85
Power Quality Batteries	100	250	40			0.85
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
Fuel Cell/Underground Storage	1	500	50	300	112.5	0.59
Hydrogen engine/Gas Storage	15	350	40	300	112.5	0.44

Table 4. Comparison of Commercial Maturity and Cost Certainty for Energy Storage Technologies

Technology	Commercial Maturity	Cost Certainty
Lead-Acid Batteries	Green	Green
Power Quality Batteries	Red	Yellow
Advanced Batteries	Red	Red
Micro-SMES	Yellow	Yellow
Mid-size SMES	Purple	Purple
Superconducting Magnetic Energy Storage (SMES)	Purple	Purple
Flywheel (high-speed)	Red	Red
Flywheel (low-speed)	Yellow	Green
Supercapacitor	Red	Red
Compressed Air Energy Storage (CAES)	Yellow	Yellow
Compressed Air Storage (CAS) in tanks	Purple	Purple
Pumped Hydro	Green	Yellow
Fuel Cells (conventional)	Yellow	Yellow
Fuel Cells (dynamic response for power quality)	Red	Red
Hydrogen combustion engine	Yellow	Green

Legend for Table 4

Color	Commercial Maturity	Cost Certainty
Green	Mature products, many sold	Price list available
Yellow	Commercial products, multiple units in the field	Price quotes available
Red	Prototype units in the field	Costs determined each project
Purple	Designs available	Costs estimated

4. Results

4.1 Performance Fit

Technologies can be matched to applications in a variety of ways. Certainly cost can be a deciding factor; this will be illustrated in the next subsection. 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 5 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.

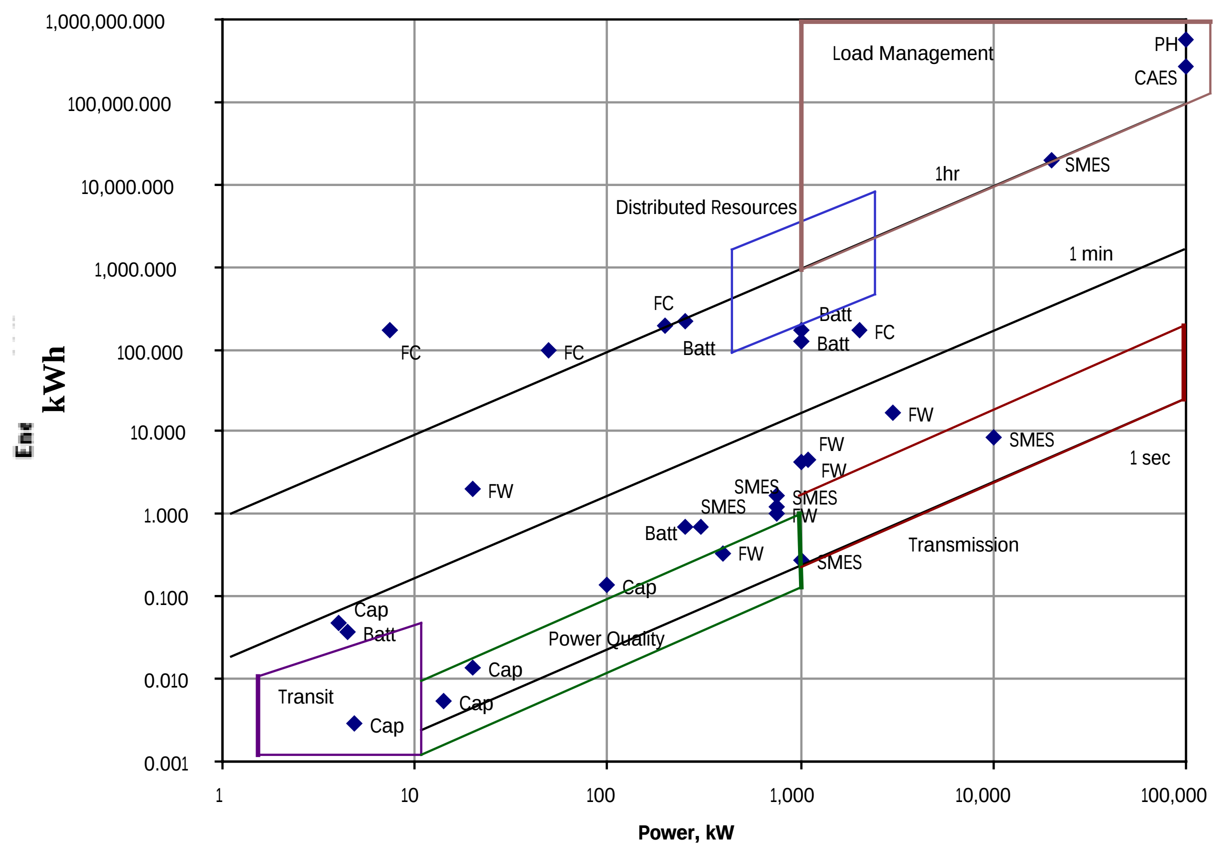

Figure 5. Power and Energy Characteristics of Energy Storage Products.

Legend for Figure 5

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

Some general conclusions from Figure 5 are:

- Supercapacitors are best suited for smaller applications, i.e., end-use.
- Batteries and SMES cover the broadest range of applications, from less than a MW to thousands of MW.
- For very high power and energy applications, only a few technologies are suitable – CAES and pumped hydro.

Figure 6 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. [21]

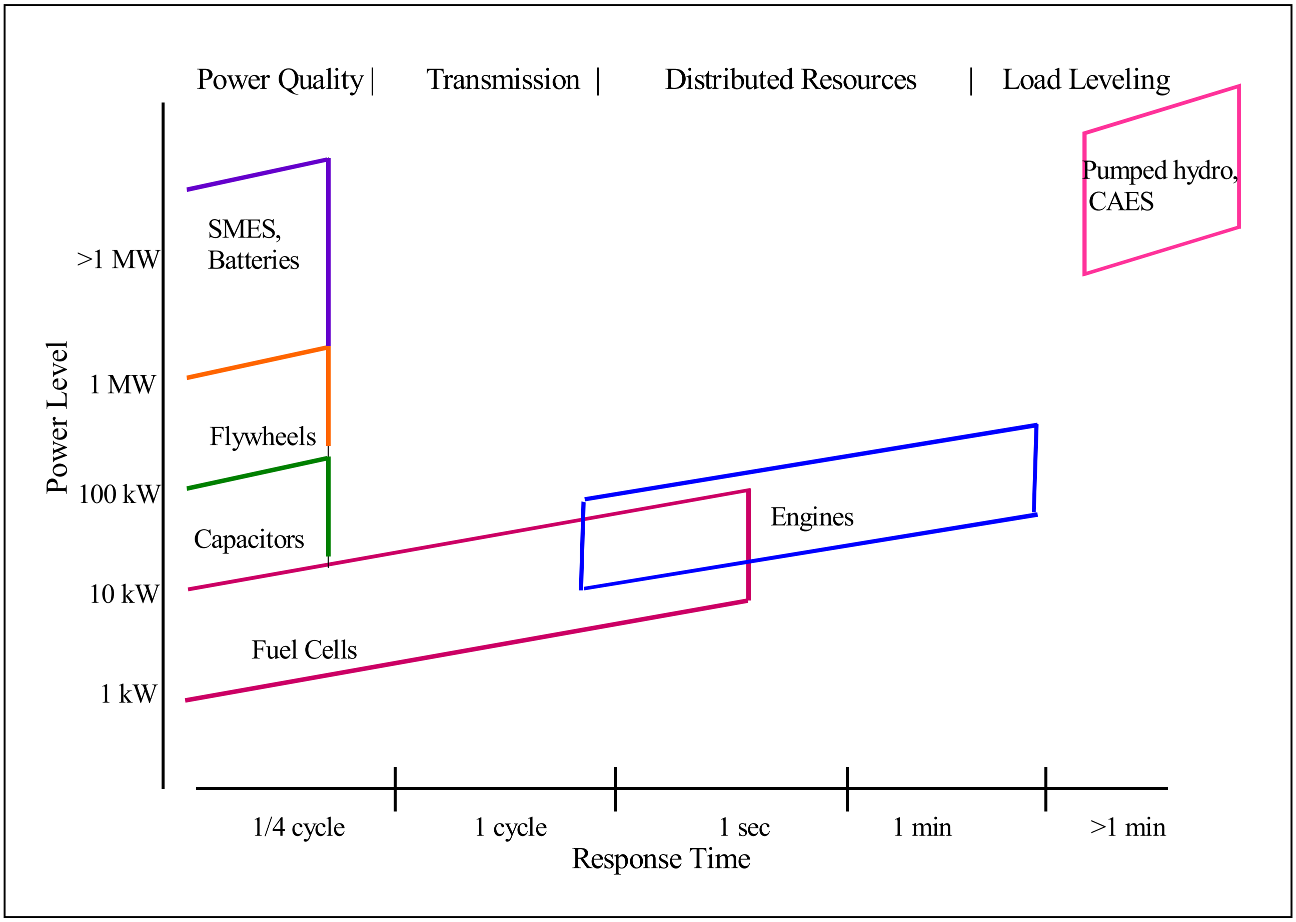

Figure 6. Response Characteristics of Energy Storage Systems.

4.2 Capital Cost

Using the analytical approach described previously in Section 3.4, 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 7-12. 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. The following is a guide to the Figures:

Figure 7: Power quality (very short time: 0 – 20 sec)

Figure 8: Transmission support (very short time: 0 – 20 sec)

Figure 9: Distributed resources / renewables matching applications (short time: 10 min. to 2 hours)

Figure 10: Expanded view of distributed resource applications (30 – 60 min.)

Figure 11: Load management (long duration: 1 – 8 hrs)

Figure 12: Battery and hydrogen comparison for load management (1 – 8 hrs)

Figure 13: Remote renewables or seasonal storage (very long duration: 1 – 7 days)

Figure 14: Comparison of hydrogen-fueled combustion engine for distributed resource applications

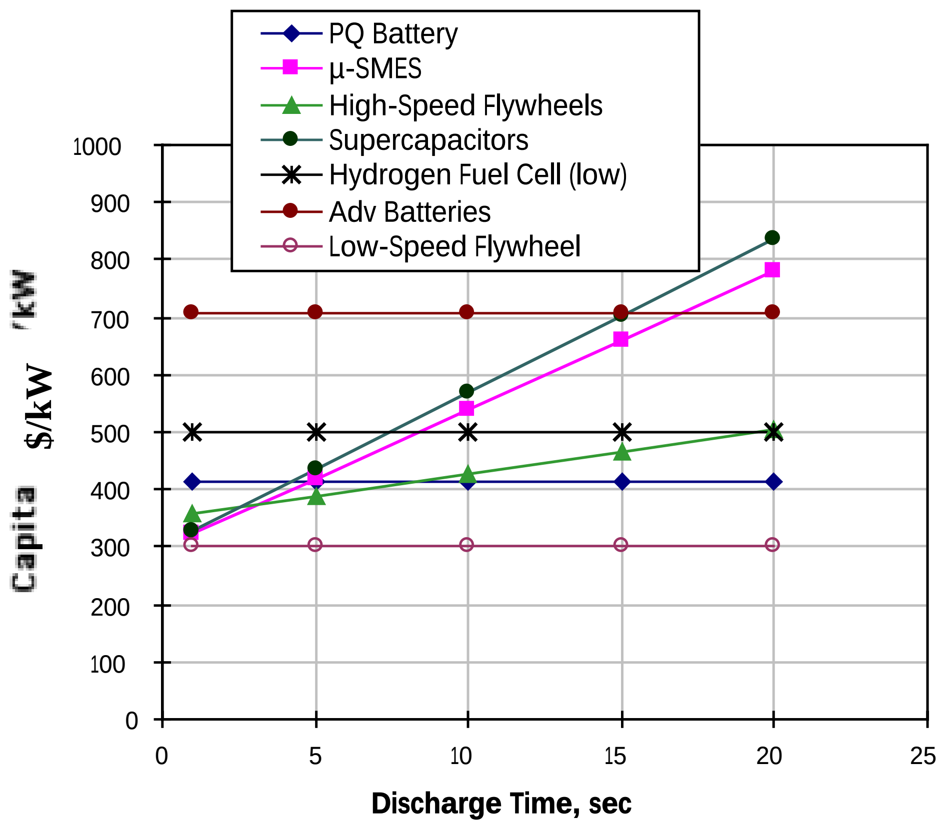

Figure 7. Power Quality (very short time: 0 - 20 sec, 1 – 4 MW).

Figure 7 shows that in the power quality application area, quite a few different technologies compete on cost for short-term storage. Although the low-speed flywheel appears quite attractive, it is very bulky and would grow in size proportionally to the energy requirement.

Another application area which needs only very short discharge is transmission enhancement, i.e., voltage or frequency stabilization. Although the time frames are the same as for end-use power quality, the power levels are significantly higher: a minimum of 20 MW. Figure 8 shows the capital cost of systems suitable for transmission applications.

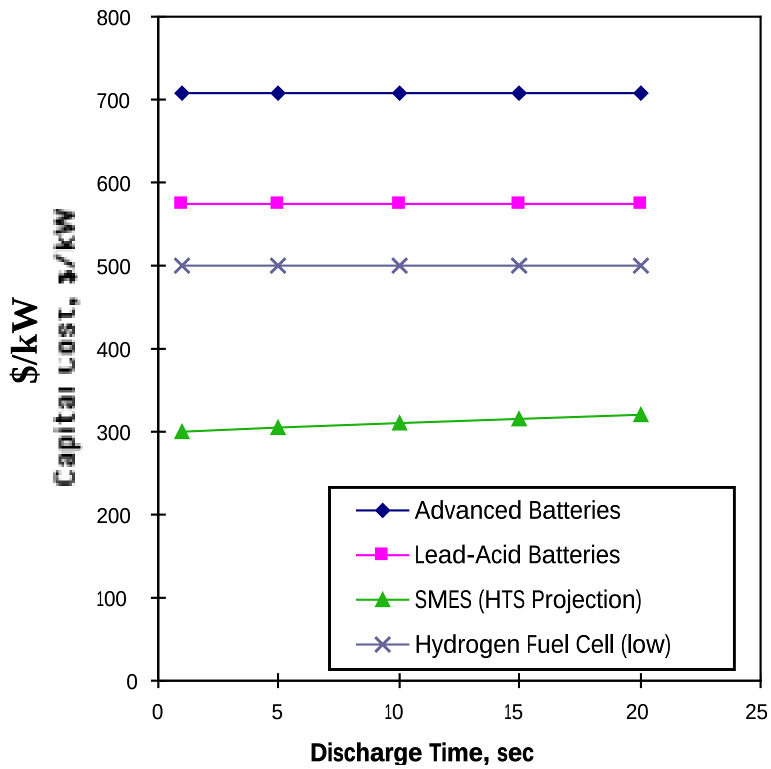

Figure 8. Transmission Support (very short time: < 20 sec, >20 MW).

The next category of results is for short- or intermediate amounts of storage, i.e., discharge durations of minutes up to 2 hours. The applications in this category include distribution system peak-shaving (i.e., conventional distributed resource applications), renewables matching, and spinning reserve. Figure 9 shows the capital cost results for the many energy storage technologies which can address these applications.

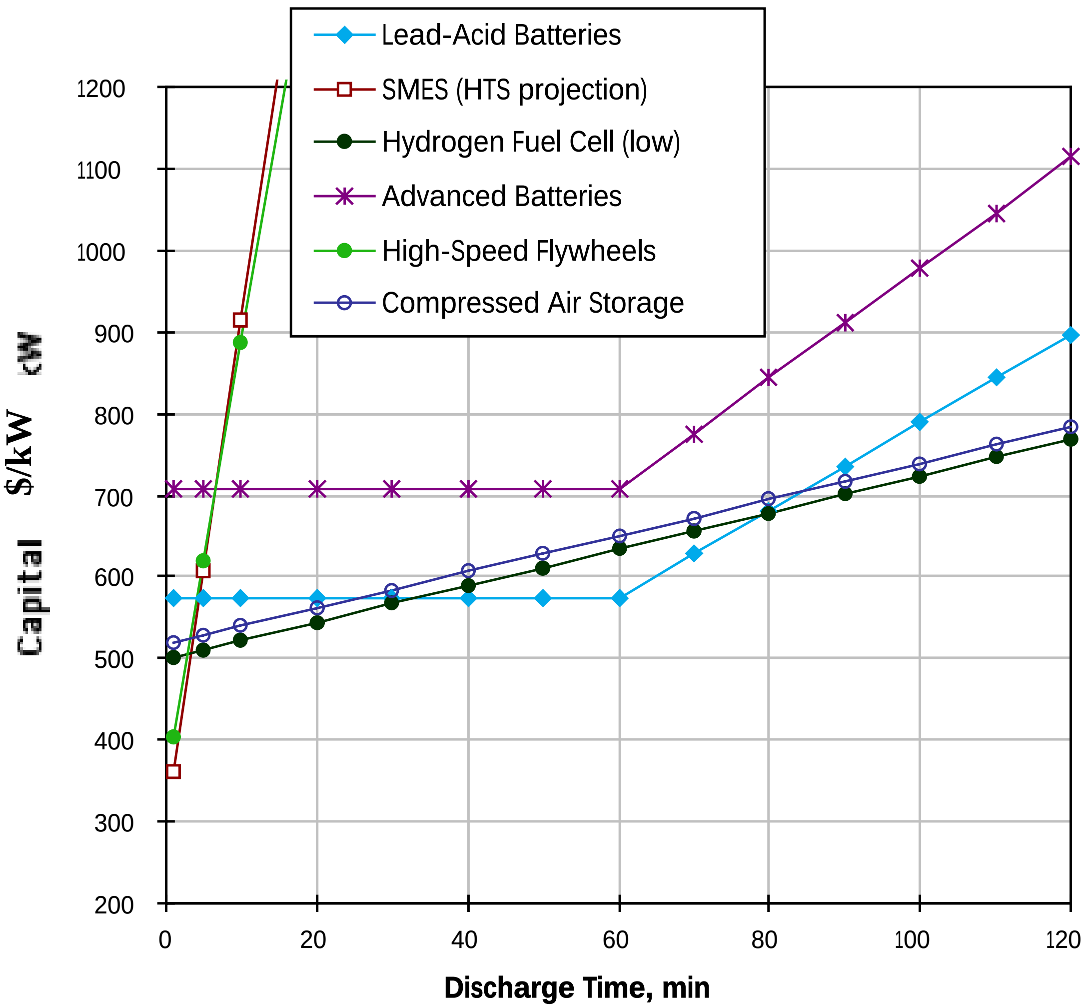

Figure 9. Distributed Utility Applications and Renewables Matching (short time: 10 min. to 2 hours, <2 MW).

Figure 10 is an expanded view of the previous chart for the time frame from 30 minutes up to 1 hr. It shows only the curves for the hydrogen engine, low-speed flywheel, hydrogen fuel cell, compressed air storage in tanks, and both lead-acid and advanced batteries.

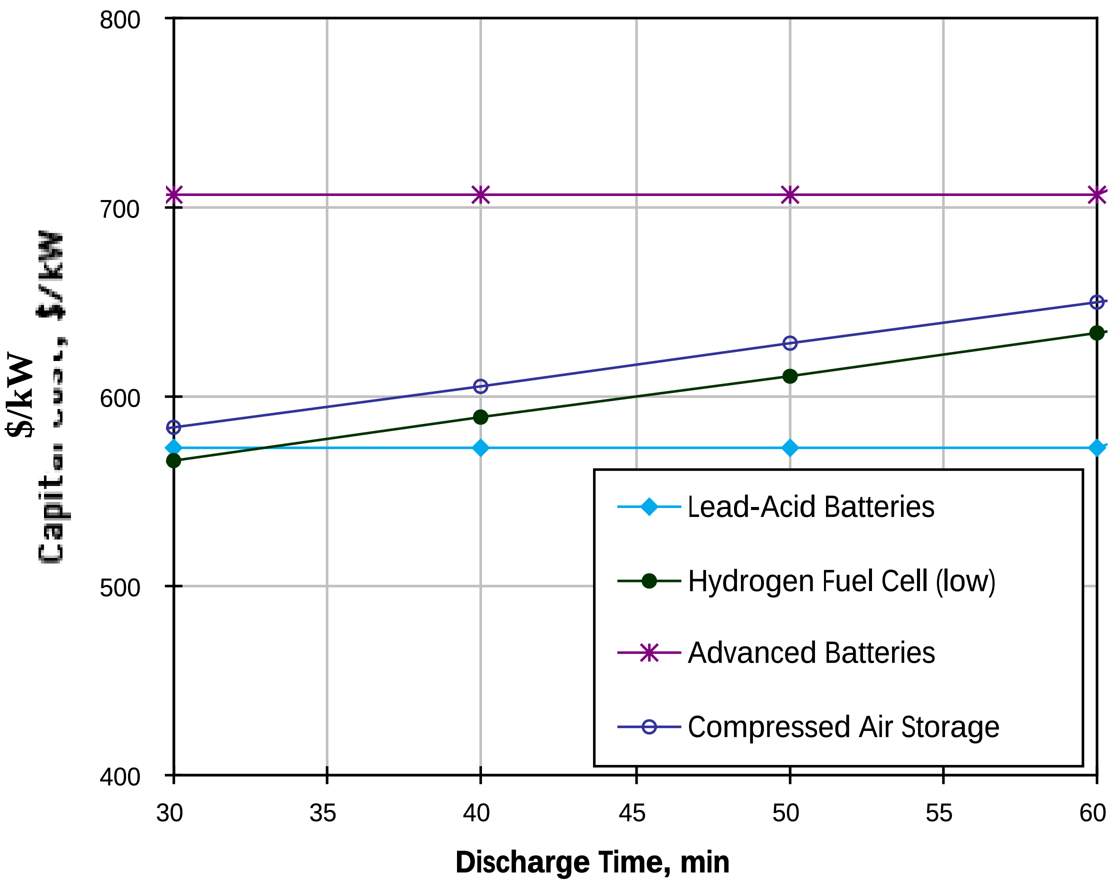

Figure 10. Expanded View of Distributed Resource Applications (30 – 60 min., <2MW).

Some observations from Figures 9 and 10 are:

- At the short-time end, a low-cost fuel cell looks good.
- At longer times, lead-acid batteries look good, until the cost curve crosses over again, as shown previously in Figure 9.

- Compressed air storage with small turbine generation can play a role in this application area.

Figure 11 shows results for long-term applications, i.e., load management and specifically load-leveling. In this figure, the $/kW basis is somewhat misleading because the storage costs ($/kWh) begin to dominate. For long-term storage, i.e., load management applications, the two traditional technologies, pumped hydro and CAES are least costly. However, they can have serious siting limitations. The next most attractive, on a capital cost basis, is the hydrogen fuel cell, and then compressed air storage in tanks with turbine generators. These three have the common feature of being fuel-based technologies. In this case, the capital cost comparison with electric storage technologies (batteries and SMES) is again misleading, because fuel-related operating costs are not taken into account. Life cycle cost analysis, which considers fuel costs, off-peak charging costs, and energy efficiencies, could make these three choices less attractive compared with batteries and SMES.

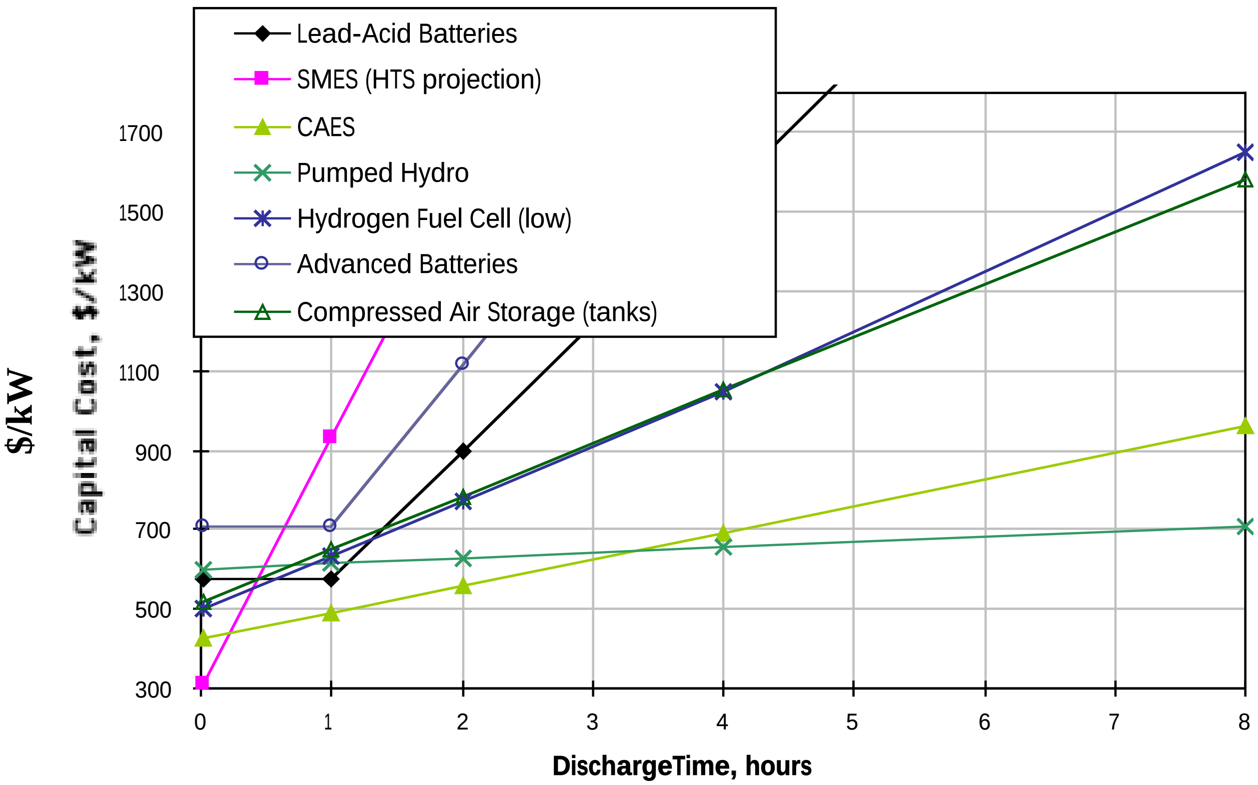

Figure 11. Load Management (long duration: 1 – 8 hrs, >10MW).

Figure 12 highlights several load management technologies: lead-acid batteries compared with fuel cells. In this chart, the batteries and fuel cells each are plotted for high and low values of capital cost. The low cross-over occurs at about 2.5 hrs and the high cross-over at about 6.5 hrs. The general conclusion is that hydrogen fuel cell systems are more suitable for longer-term applications. The cross-over points vary from a previous study [16] because the electrolyzer is sized to recharge over the entire period when discharge is not required, as discussed previously in section 3.4.

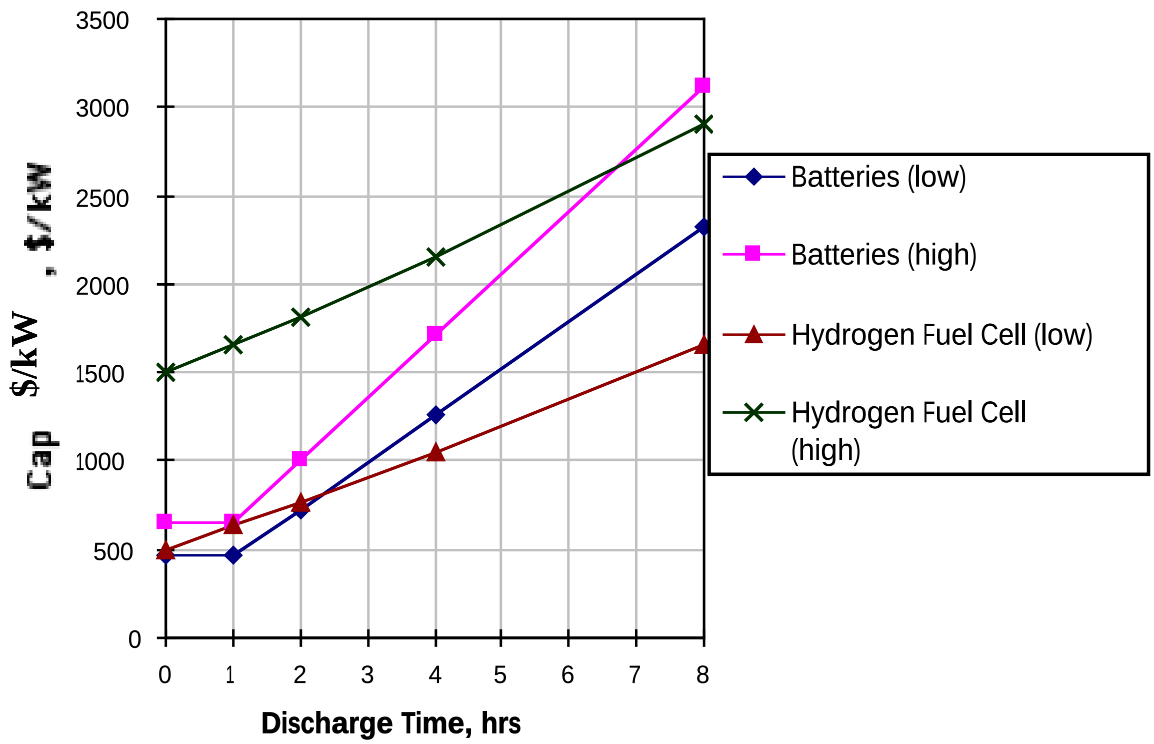

Figure 12. Battery and Hydrogen Comparison for Load Management (1 – 8 hrs).

A comparison was also made for very long-term storage. Applications that might require days worth of storage are:

- Remote locations, e.g. at the end of a feeder, which could be without power for several days.
- Villages relying on renewables, which could be unavailable for days at a time.
- "Seasonal storage" for locations with dramatic seasonal peak loads due to hot or cold weather.

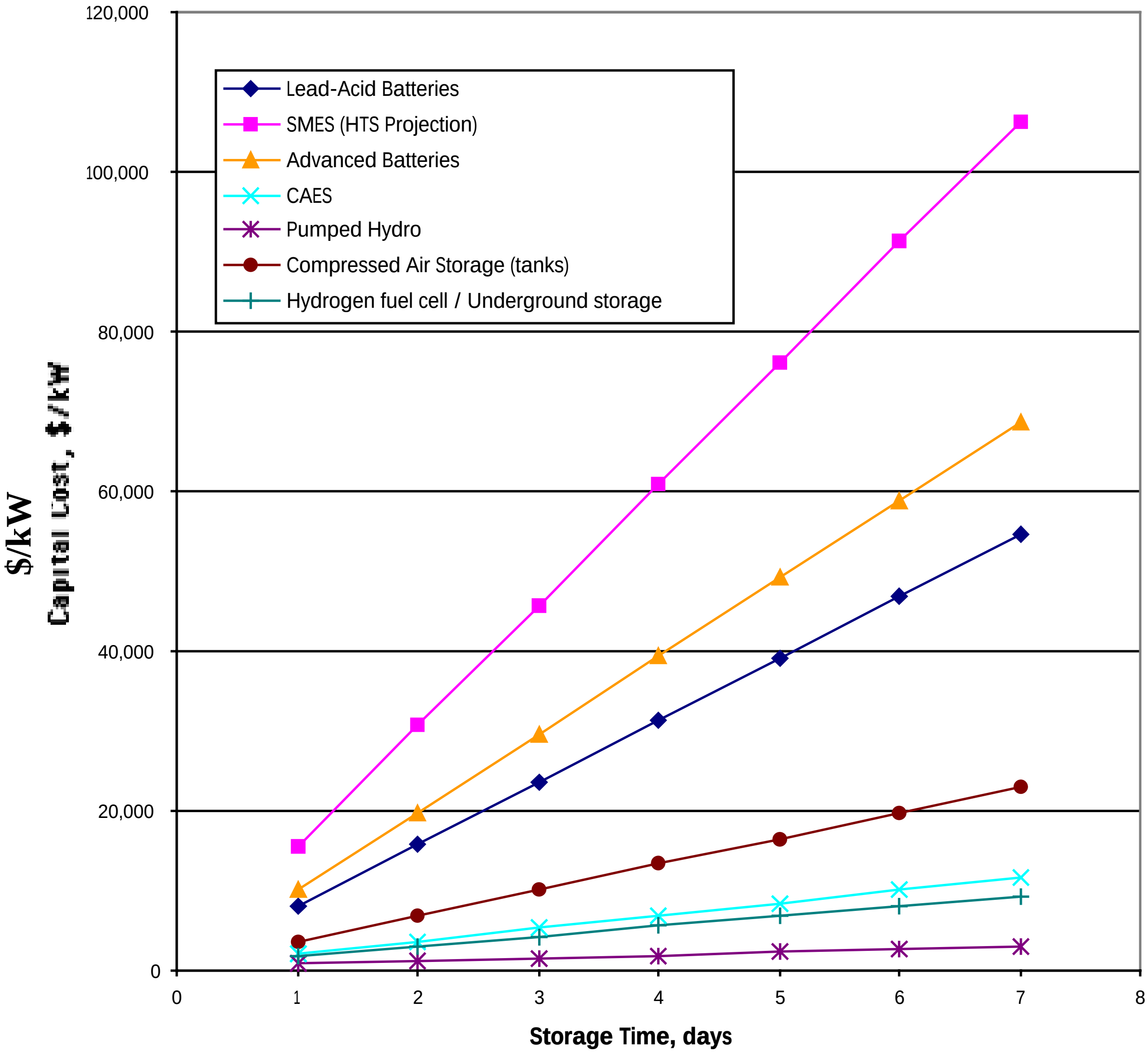

Figure 13. Remote Renewables or Seasonal Storage (very long duration: 1 – 7 days, >1MW).

Figure 13 shows similar results to Figure 11 for hours of load management. All the technologies become expensive, but those with "geologic" reservoirs (pumped hydro, CAES, underground hydrogen storage) are least expensive. Life cycle cost analysis might change the picture somewhat, but not if these systems are simply used to hold energy in reserve and only cycle once or twice a year.

Finally, a comparison is made with hydrogen-fueled combustion engines for distributed utility or renewables matching. The analysis is similar to that for the fuel cell and assumes the same electrolyzer and storage components. The results, shown in Figure 14, indicate that the engine is a very competitive solution for this application.

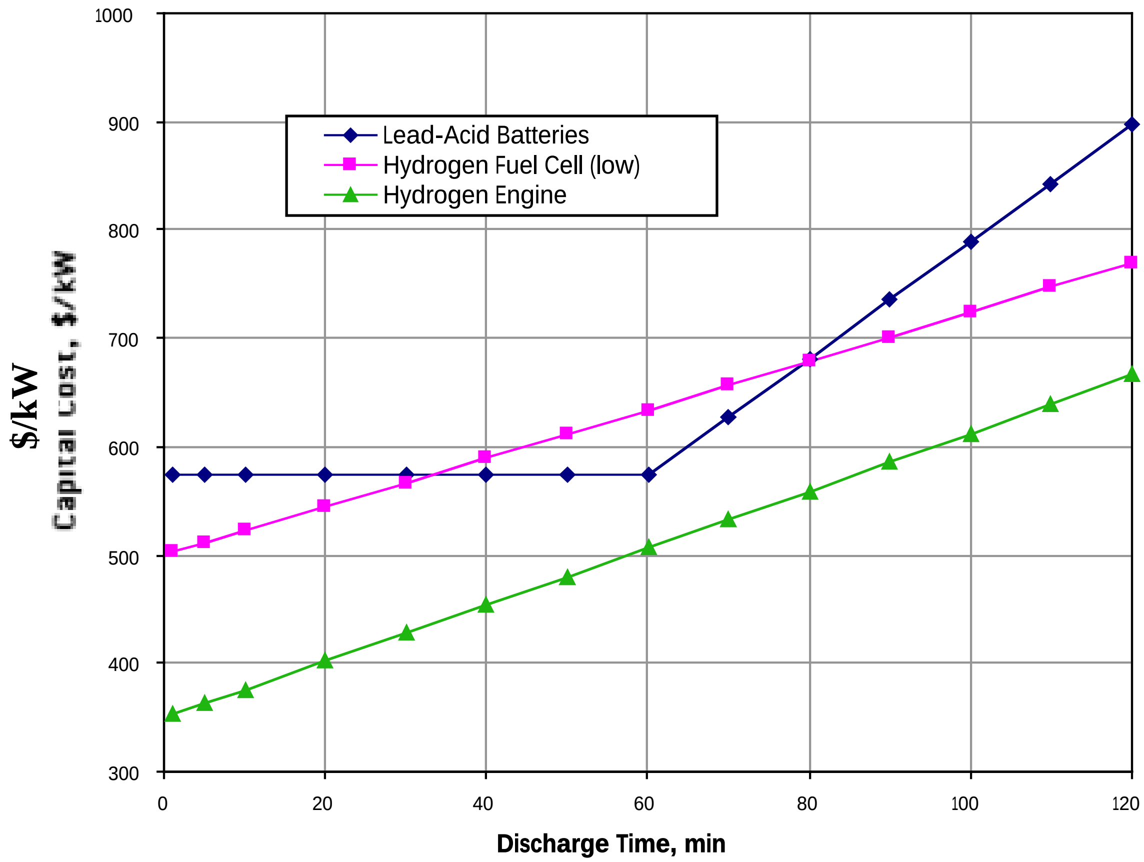

Figure 14. Comparison of Hydrogen-Fueled Combustion Engine (at today's prices) with Fuel Cell and Batteries for Distributed Resources and Renewables Matching Applications.

After considering the performance fit and capital costs, Table 5 is presented to summarize the technologies that best fit the various applications. This is similar to Table 1, with the addition of the final column.

Table 5. Applications and Appropriate Technology

APPLICATION	Power	Storage Time	Energy	Response Time	Technologies
Very short duration			kWh		
End-use ride-through, Power Quality, Motor Starting	≤ 1 MW	secs	~0.2	< 1/4 cycle	Flywheel Supercapacitors Micro-SMES Lead-acid battery H2 fuel cell
Transit	< 1 MW	secs	~0.2	< 1 cycle	Flywheel Supercapacitors Micro-SMES Lead-acid battery H2 fuel cell
T&D stabilization	up to 100's MW	secs	20 - 50	< 1/4 cycle	SMES H2 fuel cell Lead-acid battery
Short duration			kWh		
Distributed generation (peaking)	.5 to 5 MW	~1 hr	5000 - 50,000	< 1 min	Flywheel Advanced batteries SMES Lead-acid batteries Fuel cell or engine CAS
End-use peak shaving (to avoid demand charges)	< 1 MW	~1 hr	1000	< 1 min	Flywheel Advanced batteries Lead-acid batteries SMES Fuel cell or engine CAS
Spinning reserve – rapid response within 3 sec to avoid automatic shift	1 - 100 MW	< 30 min	5000 - 500,000	< 3 sec	Flywheel Lead-acid battery Advanced battery SMES Fuel cell or engine CAS
Conventional – respond within 10 min	"	≤ 30 min	"	< 10 min	Flywheel Lead-acid battery Advanced battery SMES Fuel cell or engine CAES CAS Pumped hydro

Table 5 (continued)

APPLICATION	Power	Storage Time	Energy	Response Time	Technologies
Short duration, continued			kWh		
Telecommunications back-up	1-2 kW	~2 hrs	2 - 4	< 1 cycle	Flywheel Supercapacitors Lead-acid battery Advanced battery H2 fuel cell
Renewable matching (intermittent)	up to 10 MW	min- 1 hr	10 - 10,000	< 1 cycle	Flywheel Lead-acid battery Advanced battery H2 fuel cell SMES
Uninterruptible Power Supply	up to ~2 MW	~2 hrs	100 - 4000	secs	Flywheel Lead-acid battery Advanced battery SMES CAS H2 fuel cell H2 engine
Long duration			MWh		
Generation, load leveling	100's MW	6-10 hrs	100 - 1000	mins	SMES Lead-acid battery Advanced battery Pumped hydro CAES CAS H2 fuel cell H2 engine
Ramping, load following	100's MW	several hrs	100 - 1000	< cycle	SMES Lead-acid battery Advanced battery H2 fuel cell
Very long duration			MWh		
Emergency back-up	1 MW	24 hrs	24	sec - mins	Lead-acid battery H2 engine H2 fuel cell CAS Advanced battery
Seasonal storage	50-300 MW	weeks	10,000 - 100,000	mins	CAES
Renewables back-up	100 kW -1 MW	Up to 7 days	20 - 200	sec - mins	Battery Advanced battery CAES CAS Pumped hydro H2 fuel cell with underground storage

5. Conclusions and Recommendations

5.1 Conclusions

The various energy storage technologies serve some applications better than others. Distinctions can be made on the basis of long- or short-term storage (or discharge duration), size (power level), response time, and also on the basis of cost.

– 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 peaking, 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.

– 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.

5.2 Recommendations

In this study, only capital costs were considered. It is recommended that operating costs also be considered, because the different technologies have different energy efficiencies, parasitic requirements or losses, operations and maintenance cost; some include fuel costs and different life times or replacement costs.

It is also recommended that fuel storage options for hydrogen systems be considered more broadly. In power quality applications, for example, it is possible to simply deliver hydrogen to the site, rather than use an on-site electrolyzer to produce it. This may be more cost effective. Finally, a sensitivity analysis to cost assumptions would be valuable.

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Appendix: Technology Data Sheets

The following data sheets are included in this appendix:

Battery energy storage
Superconducting magnetic energy storage (SMES)
Flywheel energy storage
Supercapacitors
Compressed air energy storage (CAES)
Pumped hydroelectric storage
Hydrogen storage

	PQ Battery	Lead-acid battery	Advanced Battery-Zn/Br	Advanced Battery-Na/S
Maximum Power Rating	4 MW	20 MW	50 kW	300 kW
Maximum Energy or Duration	30 sec	6-8 hrs	~2 hrs	~1 hr
Response Time	< 1/4 cycle	< 1/4 cycle	< 1/4 cycle	
Capital Cost:				
Energy-related, $/kWh	100	225	200	245
Power-related, $/kW	250	250	1500	259
Balance-of-Plant	50 $/kWh	~50 $/kWh	included	~40 $/kWh
Operating Features:				
Efficiency	.85	0.85	0.66	0.76
O&M-fixed		1.55 $/kW-yr	N/A	N/A
O&M-variable		1.0 ¢/kWh	"	"
Parasitic energy reqt.		small	small	5 kW/kWh stored
Lifetime/Replacement	5 yrs	5 yrs	>10 yrs	5 yrs
Size		.62 ft^2/kWh	.25 ft^2/kWh	.2 ft^2/kWh
Siting Issues:				
Environmental		lead disposal, H2	none	chemical handling
Safety		lead disposal, H2	none	chemical reaction, thermal control
Geologic		none	none	none
Technology Readiness	commercial	commercial	in test	in development
References	A1	A2	A3	A4

	micro-SMES	mid-SMES	SMES
Maximum Power Rating	6 MW	40 MW	1000 MW
Maximum Energy or Duration	~4 MJ, 1 sec	1 min - 1/2 hr	~5 hrs
Response Time	< 1/4 cycle	< 1/4 cycle	< 1/4 cycle
Capital Cost:			
Energy-related, $/kWh	72,000	2000	500
Power-related, $/kW	300	300	300
Balance-of-Plant	~10M $/MWh	~1.5M $/MWh	~.1M $/MWh
Operating Features:			
Efficiency	0.95	0.95	0.95
O&M-fixed	26 $/kW-yr	8 $/kW-yr	1 $/kW-yr
O&M-variable	2 ¢/kWh	.5 ¢/kWh	.1 ¢/kWh
Parasitic energy reqt.	~4%	1%	~1/2%
Lifetime/Replacement	30 yrs	30 yrs	30 yrs
Size	~280 ft^2/kWh	~65 ft^2/kWh	~10 ft^2/kWh
Siting Issues:			
Environmental	benign	benign	benign
Safety	magnetic field	magnetic field	magnetic field
Geologic	no requirement	no requirement	suitable for high pressure
Technology Readiness	commercial	design concept	design concept
References	A5	A6, A7	A8, A9

	Flywheels: low-speed	Flywheels: high-speed
Maximum Power Rating	1650 kW	750 kW
Maximum Energy or Duration	3 - 120 sec	~1 hour
Response Time	< 1 cycle	< 1 cycle
Capital Cost:		
Energy-related, $/kWh	300	25,000
Power-related, $/kW	300	350
Balance-of-Plant	~80 $/kWh	~1000 $/kWh
Operating Features:		
Efficiency	0.9	0.93
O&M-fixed		7.5 $/kW-yr
O&M-variable		0.4 ¢/kWh
Parasitic energy reqt.	~1%	30 W/kW
Lifetime/Replacement	20 yrs	20 yrs
Size	6.6 ft^2/kWh	3 - 4 ft^2/kWh
Siting Issues:		
Environmental	none	none
Safety	containment	containment
Geologic	none	none
Technology Readiness	commercial products	prototypes in testing
References	A10, A11	A12, A13

	Supercapacitors
Maximum Power Rating	100 kW
Maximum Energy or Duration	10 sec
Response Time	< 1/4 cycle
Capital Cost:	
Energy-related, $/kWh	82,000
Power-related, $/kW	300
Balance-of-Plant	10,000 $/kWh
Operating Features:	
Efficiency	0.95
O&M-fixed	5.55 $/kW-yr
O&M-variable	0.5 ¢/kWh
Parasitic energy requirement	negligible
Lifetime/Replacement	10,000 cycles
Size	4.6 ft^2/kWh
Siting Issues:	
Environmental	none
Safety	none
Geologic	none
Technology Readiness	several commercial products, few systems
References	A14

	Compressed Air Energy Storage (in aquifer)	Compressed Air Storage (in vessels)
Maximum Power Rating	220 MW	50-100 MW
Maximum Energy or Duration	days	~ 4hrs
Response Time	sec - min	sec - min
Capital Cost:		
Energy-related, $/kWh	3	50 $/kWh min
Power-related, $/kW	425	517
Balance-of-Plant	50 $/kWh	40 $/kWh
Operating Features:		
Efficiency	1/.08	1/.08
O&M-fixed	1.42 $/kW-y	3.77 $/kW-y
O&M-variable	.01 ¢/kWh	.27 ¢/kWh
Parasitic energy reqt.	-	-
Lifetime/Replacement	30 yrs	30 yrs
Size	1.1 ft^2/kWh	2 - 3 ft^2/kWh
Siting Issues:		
Environmental	gas emissions	gas emissions
Safety	none	pressure vessels
Geologic	required reservoir	none
Technology Readiness	commercial	concept
References	A15	A16, A17

	Pumped Hydro
Maximum Power Rating	4000 MW
Maximum Energy or Duration	~12 hrs
Response Time	minutes
Capital Cost:	
Energy-related, $/kWh	12
Power-related, $/kW	600
Balance-of-Plant	included
Operating Features:	
Efficiency	0.87
O&M-fixed	3.8 $/kW-yr
O&M-variable	.38 ¢/kWh
Parasitic energy reqt.	Evaporation losses
Lifetime/Replacement	30 yrs
Size	~2 ft^2/kWh
Siting Issues:	
Environmental	reservoir, changing water level
Safety	exclusion area
Geologic	elevation change required
Technology Readiness	mature
References	A18

	H_2 Fuel Cell	H_2 Engine
Maximum Power Rating	200 kW	1 - 2 MW
Maximum Energy or Duration	hrs, as needed	hrs, as needed
Response Time	< 1/4 cycle	seconds
Capital Cost:		
Energy-related, $/kWh	15	15
Power-related, $/kW	500	300
Balance-of-Plant	N/A	N/A
Operating Features:		
Efficiency	0.59	0.44
O&M-fixed	10.0 $/kW-yr	.7 $/kW-yr
O&M-variable	1.0 ¢/kWh	.77 ¢/kWh
Parasitic energy reqt.	N/A	N/A
Lifetime/Replacement	20 yrs	20 yrs
Size	.3 - .6 ft^2/kW	.05 - .06 ft^2/kW
Siting Issues:		
Environmental	none	emissions
Safety	none	none
Geologic	none	none
Technology Readiness	in test	available for demonstration
References	A19	A20

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