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Long vs. Short-Term Energy Storage: Sensitivity Analysis

A Study for the DOE Energy Storage Systems Program

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Long vs. Short-Term Energy Storage: Sensitivity Analysis*

A Study for the DOE Energy Storage Systems Program

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Abstract

This report extends earlier work to characterize long-duration and short-duration energy storage technologies, primarily on the basis of life-cycle cost, and to investigate sensitivities to various input assumptions. Another technology – asymmetric lead-carbon capacitors – has also been added. Energy storage technologies are examined for three application categories – bulk energy storage, distributed generation, and power quality – with significant variations in discharge time and storage capacity. Sensitivity analyses include cost of electricity and natural gas, and system life, which impacts replacement costs and capital carrying charges. Results are presented in terms of annual cost, $/kW-yr. A major variable affecting system cost is hours of storage available for discharge.

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Acronyms and Abbreviations

AEP	American Electric Power
BoP	balance of plant
BTU	British thermal unit
CAS	compressed air storage (surface CAES)
CAES	compressed air energy storage
DG	distributed generation
DOE	Department Of Energy
EDL	electronic double layer
ESS	Energy Storage Systems
L/A	lead-acid
LAC	levelized annual cost
Li-ion	lithium-ion
Na/S	sodium/sulfur
Ni/Cd	nickel/cadmium
Ni/MH	nickel metal hydride
O&M	operation and maintenance
Pb-C	lead-carbon
PCS	power conversion system
PQ	power quality
SMES	superconducting magnetic energy storage
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 work described in Sandia Report SAND2003-2783, "Long- vs. Short-term Energy Storage Technologies Analysis: A Life-Cycle Cost Study", which was in turn a follow-on to Sandia Report SAND2001-0765, "Characteristics and Technologies for Long- vs. Short-term Energy Storage." In the first study, energy storage technologies were compared on the basis of power and storage capacity ratings, time response, and capital costs. In the second study, life-cycle cost analysis was added to include the effects of efficiency, operating costs, and replacement costs. In this current study, a sensitivity analysis has been added to consider variations in the costs of consumables and expected system life. Throughout this work, a specific objective has been to distinguish energy storage technologies on the basis of discharge time: short vs. long.

The storage technologies included in this study are asymmetric lead-carbon high energy density capacitors, in addition to all the technologies previously considered: 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 to the specifications of three application categories were compared:

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

Some conclusions from this study are:

- Life-cycle cost analysis provides critical information that is not available from capital cost analysis alone, especially for distributed generation and bulk energy storage systems.
- Power quality system costs are dominated by capital cost, and are very sensitive to system life, mostly due to capital carrying charges.
- At current prices, lead-carbon capacitors compare with some of the more expensive technologies for both bulk storage and distributed generation applications. If projected large-scale production prices are achieved, they will compare with some of the least expensive technologies.
- All technologies show some sensitivity to electricity prices, especially those with lower efficiencies.
- As assessed in the study, natural gas prices affect only CAES systems, but they might also be reflected in electricity prices.
- System life assumptions significantly impact the annual capital carrying cost.
- System life also significantly impacts the need for component replacement and the inclusion of associated costs.
- The savings in replacement cost are generally offset by the additional annual carrying cost, however, so the technology comparison is only modestly affected. Technology selection should be based on the system life desired by the user.

1 Introduction

1.1 Background and Objectives

The United States Department of Energy (DOE), through the Energy Storage Systems (ESS) Program at Sandia National Laboratories is working with the electric utility industry and the manufacturing sectors to develop energy storage systems for many applications of interest. 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 capabilities of various types of technologies.

A previous study [1] compared energy storage technologies with different discharge times on the basis of life-cycle costs. This study was an extension of the work presented in an earlier study.[2] The current effort continues the analysis and investigates the sensitivities of some of the input parameters, including the cost of consumables and the expected system life.

The overall goal of this project is to elucidate matches between applications and storage technologies by examining performance characteristics and costs compared to requirements. The objectives of this study were to:

- Add another technology to the comparison, and
- Investigate the sensitivity of the results and conclusions to a number of input assumptions.

Further, a detailed analysis of the additional technology, asymmetric lead-carbon high energy density capacitors, is included.

1.2 Relationship to Previous Studies

This study extends the work of the previous two studies mentioned above which emphasized life-cycle costs and capital costs, respectively. The earlier studies included the comparison of the effects of efficiency differences, operation and maintenance (O&M) costs, parasitic losses, and replacement requirements that arise from different cycle or shelf lives. Introducing these operational differences paints a different picture of the life-cycle costs of the various technologies as compared to using just capital costs. However, we wondered if certain assumptions in the previous study could impact the conclusions, and so this current work includes a sensitivity analysis on the cost of consumables (electricity and natural gas) and expected system life. The latter is particularly interesting because parallel benefit studies used a 10-year life, while previous analyses in this series used a 20-year life. The benefit studies have been carried out by Distributed Utility Associates (DUA).[3] In this current study, no other assumptions have been changed; i.e., all capital costs, efficiencies, and operating costs remain as before. Figure 1 shows the relationships of the various studies.

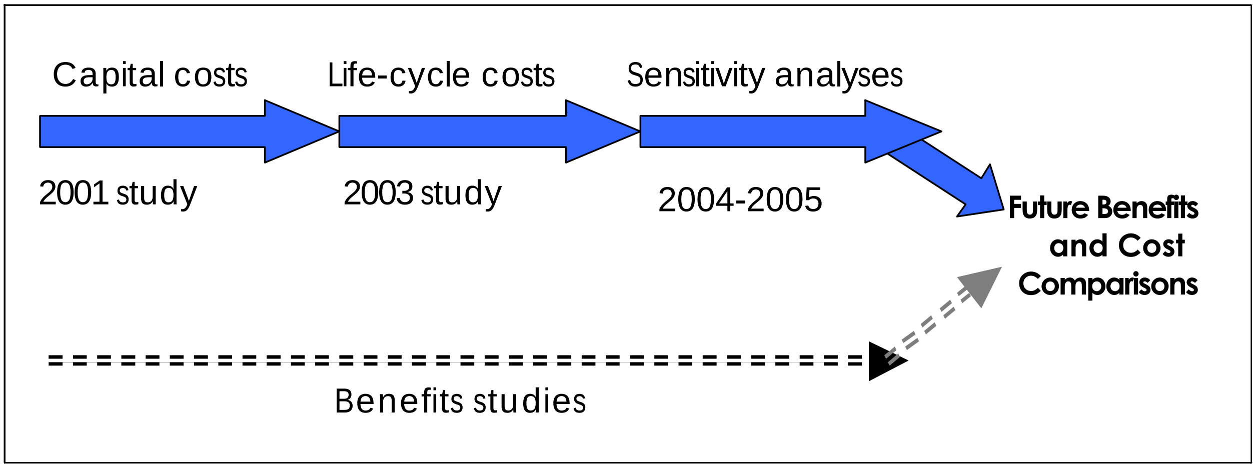


Figure 1. Relationships of Current Study to Previous and Parallel Studies.

1.3 Contents of This Report

This report includes a review of some previous material, and refers significantly to earlier work. It also includes new material as indicated below:

- Review of applications and technologies from previous studies
- Review of analysis approach
- Comments on original results
- Analysis of another technology – asymmetric lead-carbon capacitors
- Sensitivity study results

2 Review

2.1 Applications

For this study, the applications of interest have been classified as bulk energy storage for the purpose of load-leveling (typically diurnal) or load management, distributed generation (DG) for peak shaving, and power quality (PQ) for high end-use reliability. These applications correspond to the categories of the previous studies and also approximately to the categories of the Phase II Opportunities Analysis.[4] 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 (0.05 - 8 MWh)	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

2.2 Technologies and Systems

The technology types considered in this study are the following:

- Lead-acid (L/A) batteries (flooded)
- Valve-regulated lead-acid batteries (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
- Small-scale superconducting magnetic energy storage (micro-SMES)
- Low speed flywheels (steel wheels)
- High speed flywheels (composite wheels)
- Super-capacitors
- Compressed air energy storage (CAES) in underground caverns

- Compressed air storage in surface vessels (surface CAES, referred to as CAS in previous reports)
- Pumped hydroelectric storage
- Hydrogen storage used with either a hydrogen fuel cell or hydrogen engine
- Asymmetric lead-carbon capacitors

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.

Table 2. Technologies Considered in Each Application Category.

Bulk Energy Storage	Distributed Generation	Power Quality
Lead-acid batteries	Lead-acid batteries	Lead-acid batteries
Na/S batteries	Na/S batteries	Li-ion batteries
Regenesys	Ni/Cd	High-speed flywheels
Zn/Br batteries	Li-ion batteries	Low-speed flywheels
Ni/Cd	Zn/Br batteries	Micro-SMES
CAES	V-redox batteries	Super-capacitors
Pumped hydro	High-speed flywheels	
Asymmetric lead-carbon caps	Surface CAES	
	Asymmetric lead-carbon caps	
	Hydrogen fuel cell	
	Hydrogen engine	

2.3 Life-Cycle Cost Review

Life-cycle cost comparisons were calculated for each of the systems. 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.[5] The results can be computed as levelized annual cost, in $/kW-yr; or as a revenue requirement, in cents/kWh. In this study, results are presented only in $/kW-yr. All costs are per delivered kW-yr.

The levelized annual cost (LAC) is made up of the following terms:

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

or,

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

where:

FCR	=	Fixed Charge Rate or Carrying Charge Rate (1/yr)
TCC	=	Total Capital Cost ($/kW)
ARC	=	Annualized Replacement Costs ($/kW/yr)
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
UCe	=	Unit Cost of Input Electricity (¢/kWh)
η	=	Storage Efficiency (kWh_{out}/kWh_{in})
Le	=	Levelization Factor for Electricity
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)

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

2.4 Capital Cost Review

From equation 1, it is clear that the capital cost component is an important component of the annual cost. The detailed calculation of these costs was described in the previous report.[2] 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 cost is the sum of the component costs plus Balance of Plant (BoP) costs:

$$\text{Cost}_{\text{total}}\ (\$) = \text{Cost}_{\text{pcs}}\ (\$) + \text{Cost}_{\text{storage}}\ (\$) + \text{Cost}_{\text{Bop}}\ (\$) \qquad (2)$$

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

$$\text{Cost}_{\text{storage}}\ (\$) = \text{UnitCost}_{\text{storage}}\ (\$/\text{kWh}) \times E\ (\text{kWh}) \qquad (3)$$

where E is the stored energy capacity.

In the simplest case, E is equal to $P \times t$, where P is power and 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 3 is modified as follows:

$$\text{Cost}_{\text{storage}}\ (\$) = \text{UnitCost}_{\text{storage}}\ (\$/\text{kWh}) \times (E\ (\text{kWh}) / \eta_{\text{dis}}) \qquad (4)$$

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 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 shortest discharge time batteries considered in this study were ten-minute batteries.

The balance-of-plant costs, $Cost_{Bop}$, are typically proportional to energy capacity, but in some cases are fixed costs or are proportional to power rating. In this study, building costs were included for bulk energy storage systems, assuming a new site was likely to be prepared 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.

2.5 Economic and Operating Assumptions

The analysis requires economic assumptions in addition to the input cost and performance parameters for each technology. The economic assumptions are listed in Table 3. 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. In the original study, a system life of 20 years was assumed. This implies a levelization period of 20 years. In the sensitivity analysis discussed in Section 4, this value is parameterized to show the impact of changing this assumption.

Table 3. 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	10.6%
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%

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 operates 250 days per year (i.e., 5 days/week, 50 weeks/year). The discharge time (or the corresponding storage capacity) was a parameter of the analysis. For all technologies except hydrogen systems with a separate electrolyzer, the recharge time was assumed equal to the discharge time. 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.

One motivation for investigating life-cycle costs was the ability to include replacement costs in an annual budget. Initial capital costs do not tell the whole story for many storage technologies because of limited lifetimes or cycle lives. Some batteries are short-lived. This aspect of the technology performance showed a contrast with other systems that do not require significant replacement costs during a 20-year lifetime. In the sensitivity study, when a shorter required service life was assumed for all technologies, some of the contrast disappeared.

Most of the energy storage systems described in this report require some amount of 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 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 power conversion system (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.

2.6 Representative Results and Comments

The results from the previous study are included graphically in the report SAND2003-2783. Three figures are duplicated here as a review of the results. Figure 2 presents the components of annual cost (in $/kW-yr) for the case of bulk storage technologies designed for an 8-hour discharge time. Figure 3 presents the components of annual cost for the case of distributed generation technologies designed for a 4-hour discharge. Figure 4 presents the components of annual cost for power quality technologies designed for a 20-second discharge.

Also shown in Figures 2-4 are indications of the percentage of total cost due to capital carrying charge: the value of the blue bars in relation to the total. The significance of this value is that the capital carrying charge, while important, does not tell the whole story, i.e., the other components contribute to the life-cycle cost and need to be considered. From the numbers, it can be seen that the larger the operating time, i.e., hours of storage, the smaller the percentage of annual cost due to capital. This is mainly due to the cost of electricity for charging the storage device. Conversely, for the power quality systems, the capital costs dominate because so little energy is exchanged. Thus, decisions can be more easily justified on the basis of capital cost alone.

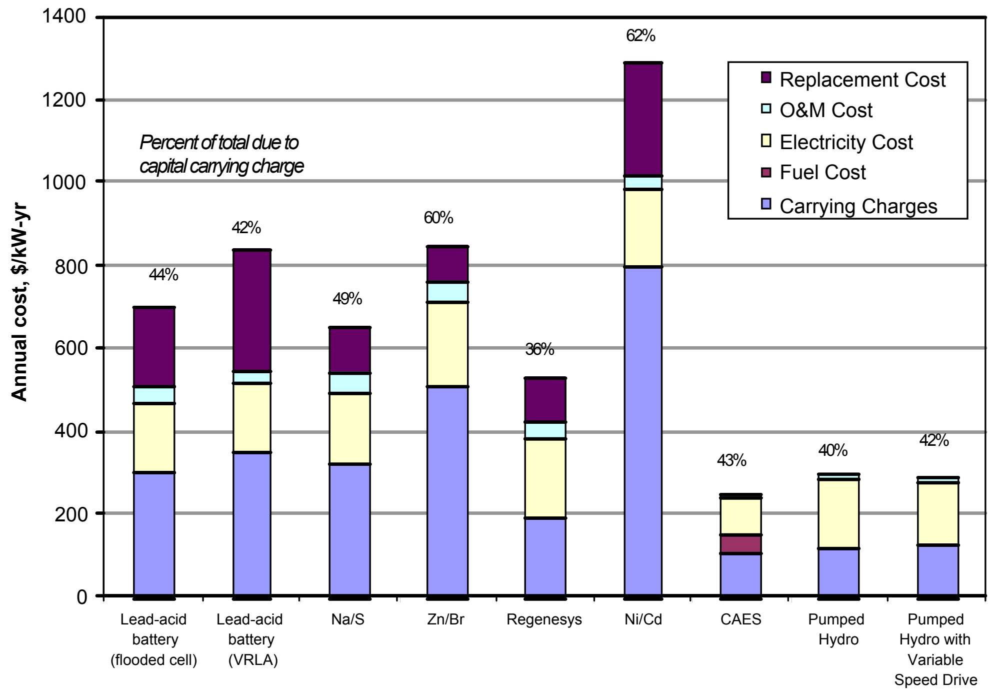


Figure 2. Annual Cost Components for 8-hr Bulk Energy Storage Technologies.

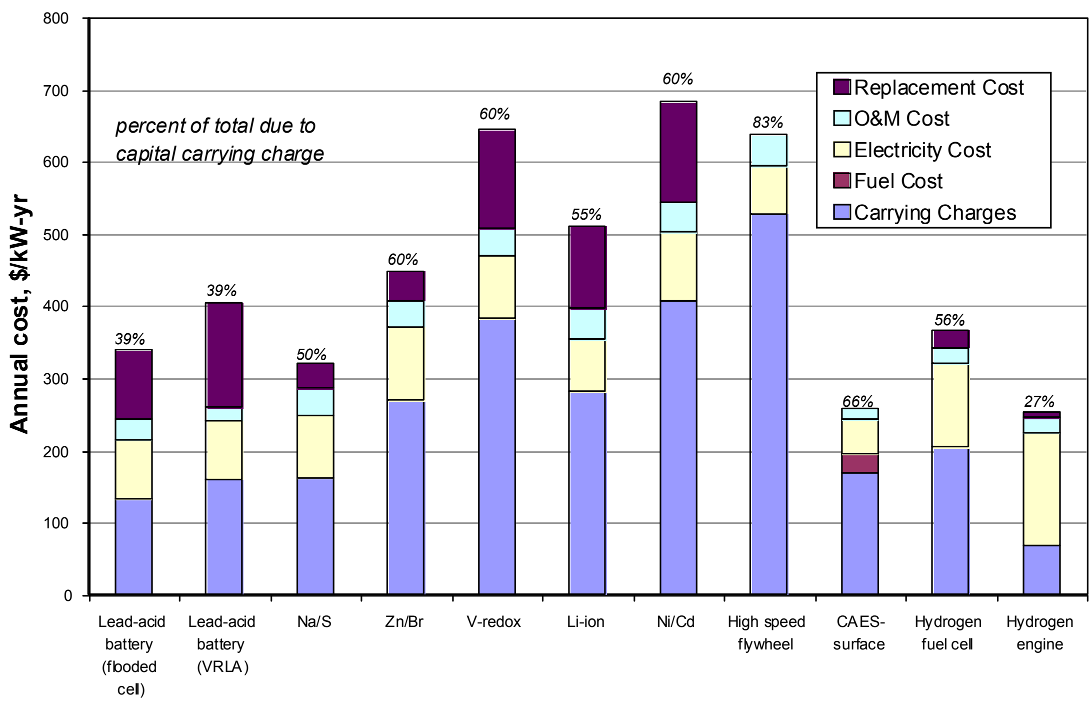


Figure 3. Annual Cost Components for 4-hr Distributed Generation Technologies (Base Case: 20-yr Life).

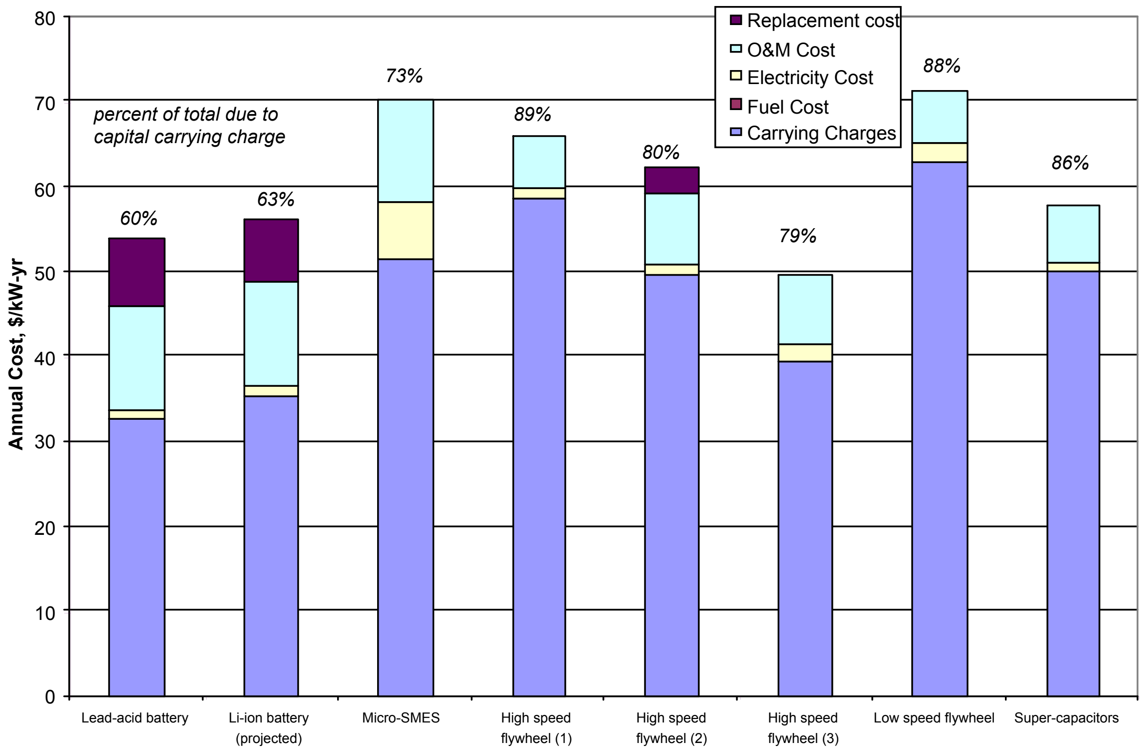


Figure 4. Annual Cost Components for 20-Second Power Quality Technologies.

3 Additional Technology: Asymmetric Lead-Carbon Capacitors

One major objective of this study was to add another technology to the analysis: asymmetric lead-carbon (Pb-C) capacitors. These capacitors are being developed for long-duration discharge (3-8 hours), as opposed to power quality capacitors, which are designed for short discharge. Figure 5 shows performance generically, in terms of specific power and specific energy, compared with some other technologies.[6] This asymmetric lead-carbon capacitor technology was added to both the bulk storage and distributed generation application categories.

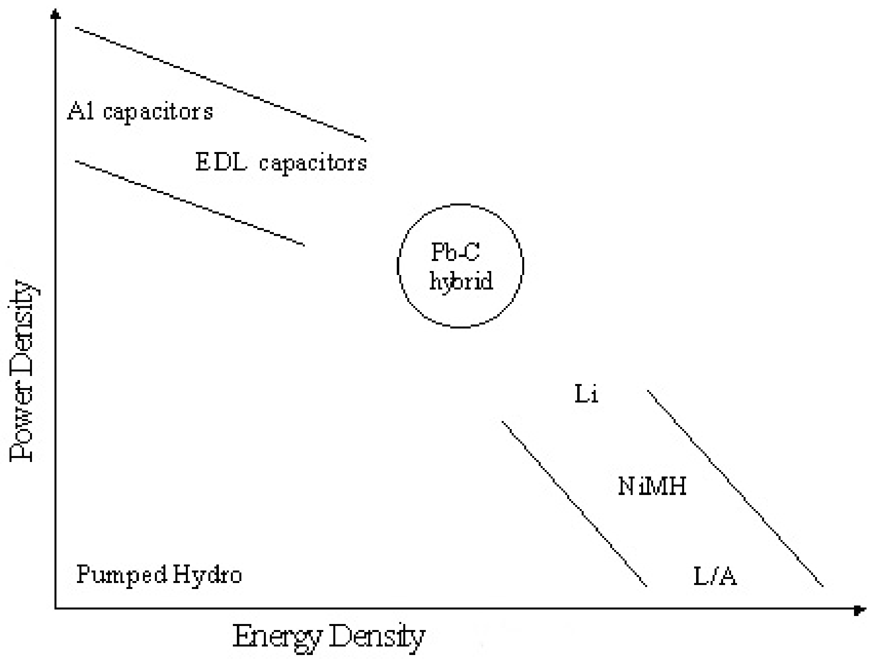
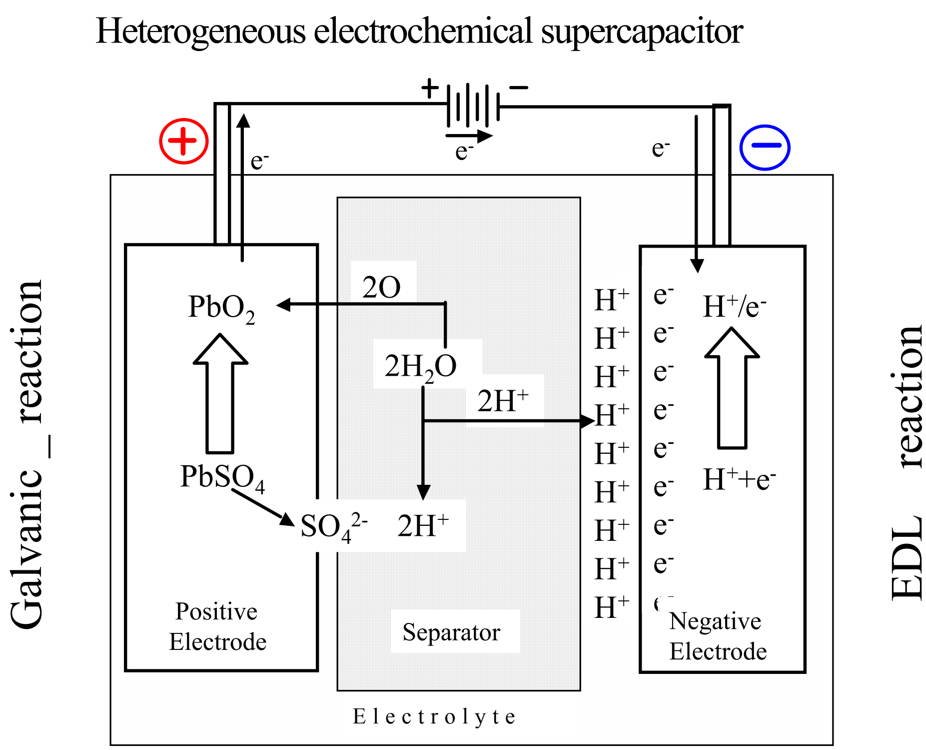


Figure 5. Approximate Energy-Power Density Relationship of Lead(Pb)-Carbon Capacitors Compared to Other Energy Storage Types. EDL is Electronic Double Layer Capacitor. L/A is Lead-Acid Battery. (Figure Modified from AEP Presentation.)

3.1 Technology Description

This section presents a summary of information on the asymmetric lead-carbon capacitor technology. A more detailed description may be found in Appendix A. It is beyond the scope of this section and even the Appendix to go into the history of the concept, the sequence of organizations that have supported its development and the many technical details under study today. Recently, American Electric Power (AEP) has been exploring this technology and has assessed its viability. That effort led to the information in Figure 5 above and Figure 6 below. The latter is a good starting point for a description of the technology. Note that the technology is a combination of different concepts and thus it may be assigned several titles, each of which portrays some of its characteristics. Here we use the terms “asymmetric lead-carbon capacitor” and the shortened version “asymmetric capacitor”, even though there are many other types of asymmetric capacitors. One of the other titles is "heterogeneous electrochemical supercapacitor", which has been used by AEP.



During Charging

Figure 6. Operation of Asymmetric Lead-Carbon Capacitor During Charge. The Positive Electrode Exhibits an Electrochemical Reaction Much like that of a Lead-Acid Battery. The Negative Electrode Undergoes no Chemical or Electrochemical Reactions and Acts Like an Electronic Double Layer Capacitor Element. (Figure Courtesy of AEP).

The concept of the asymmetric capacitor is described here, using Figure 6 as a guide. This electricity storage device is based in part on the lead-acid battery, its positive electrode consisting of the same components and having the same electrochemical function. Its negative electrode, which is essentially activated carbon, has a surface charge that can reverse polarity and whose magnitude changes with electricity storage level. The technology is best understood by considering the changes at the two electrodes during charge and discharge. When charging, an externally applied voltage causes current to flow from the negative electrode (carbon) to the positive electrode (lead). Electrons are removed from the positive electrode and flow in the opposite direction through the external circuit. As shown in the figure, the overall reaction at the positive electrode during charge may be written as:

$$PbSO_4 + 2H_2O \rightarrow PbO_2 + H_2SO_4 + 2H^+ + 2e^- .$$

The potential of the positive electrode is determined by the thermodynamic free energy of the reactants and products shown in the equation above. The potential of this electrode in an asymmetric lead-carbon capacitor is thought to be relatively constant, varying slightly with pH and temperature, according to the Nernst equation[1]. The negative electrode, on the other hand, acts much like a capacitor. Ionic charge is stored electrostatically in a double layer at the surface of the carbon. The charging process adds electrons to the carbon electrode, which changes the voltage across the double layer. The more energy that is stored in the capacitor, the more negative the voltage of the carbon electrode. The voltage across the double layer is roughly proportional to the charge level of the device. During discharge, the opposite processes occur and electrons leave the carbon. The voltage variation across the double layer causes the terminal voltage of the asymmetric capacitor to range from about 1.0 V at the practical limit of discharge, to about 2.4 V at full charge.

A key motivation for pursuing the asymmetric capacitor is the possibility that it will be able to achieve 5000 full discharges, as compared to a practical limit of about 1000 for most lead-acid battery designs. Some developers have suggested that achieving this number of full discharges would require at least three times the minimum amount of lead be included in the positive plate. (See four U.S. patents that relate to this technology: 6,222,723; 6,195,252; 6,426,862; and 6,466,429 [7]). That is, the positive plate of an asymmetric capacitor should contain between 3 and 4 times more lead than the positive plate of a lead-acid battery with the same initial electricity storage capacity. (Note that lead-acid batteries in general will also achieve a longer life with more lead but that addition would be necessary on both negative and positive plates. The resulting battery would be extremely heavy and costly.)

Activated carbon has considerable surface area, is relatively lightweight, and is thus a good choice for the negative electrode, which must have sufficient surface area to accommodate the total charge at maximum stored energy. Many grades of activated carbon are commercially available. This capacitor demands the use of relatively pure carbon with large surface area and pore sizes of 20 to 30 Å.

3.2 Costs Used in this Analysis

Since the asymmetric capacitor is based on lead-acid battery technology, a straightforward approach to estimating its cost is to use lead-acid batteries as the starting point. This allows the development of comparative costs for all elements except the carbon (negative) electrode. There is some uncertainty in the cost of the negative electrode because the cost of carbon ranges from 2$/kg to 200$/kg, depending on grain size, quality and purity. Here we assume the carbon costs about 30$/kg in small quantities today, and will decrease to about 15$/kg for large-scale production in the future. This approach leads to the costs shown in the tables below. Table 4 lists the cost components for the storage elements alone, comparing a lead-acid battery, a capacitor based on current costs, and a future, commercial capacitor. The detailed development of these values is described in Appendix A.

[1] David Linden and Thomas B. Reddy, Handbook of Batteries, Third Edition, McGraw-Hill, 2002, p. 2.10.

Table 4. Cost for Lead-Acid Batteries and Asymmetric Lead-Carbon Capacitors.

	Lead-Acid Battery	Capacitor Today	Capacitor Future/Commercial
	($/kWh)	($/kWh)	($/kWh)
Positive electrode	45	155	155
Negative electrode	45	400	100
Electrolyte	22.5	15	15
Separator	15	15	15
Case/Containment	22.5	40	40
Total	**150**	**625**	**325**

We can take these base figures from Table 4 and predict a cost for systems based on asymmetric capacitors as the electricity storage element. Overall system costs include the PCS and the balance-of-plant, which are given in Table 5 below, along with assumed performance parameters.

Table 5. Assumed Parameters for Analysis of Asymmetric Capacitors.

Parameter	Today	Future Commercial
Energy storage capital cost	625 $/kWh	325 $/kWh
Power converter capital cost	300 $/kW	150 $/kW
Balance-of-plant capital cost	200 $/kW	200 $/kW
Round-trip efficiency	75%	85%
Parasitic losses, %/day	insignificant	insignificant
Fixed O&M, $/kW-yr	5 $/kW-yr	5 $/kW-yr
Variable O&M, $/kWh	insignificant	insignificant
Cycle life	5000 cycles	5000 cycles
Replacement period	15 years	15 years
Replacement cost	625 $/kWh	325 $/kWh

Today, this type of advanced capacitor is in an early stage of development. Some models have been constructed, mainly by scientists who understand the details of the system and what is needed to make them work correctly and thus can correct any defects during assembly. From a production standpoint, the positive electrode and some aspects of the separator, electrolyte, and case are well understood by the lead-acid battery industry. Eventually, as more and more systems are constructed and the technology approaches the prototype stage, it will be necessary to move the fabrication of the negative electrode and the assembly of the entire system into a commercial status. At that time, it will be appropriate to reassess system costs. It is not known whether any of the existing cells of this type of asymmetric capacitor have achieved 5000 cycles. It is important to explore this issue early in the next stage of research.

3.3 Results

Annual cost predictions for asymmetric capacitors are shown along with other technologies in the figures that follow. Figure 7 shows the total annual cost over all discharge times considered for bulk storage applications. The asymmetric capacitor line is marked with an arrow. Figure 8 presents similar results, but for the distributed generation application and selected technologies. Note that the asymmetric capacitor at today's costs is among the more expensive technologies.

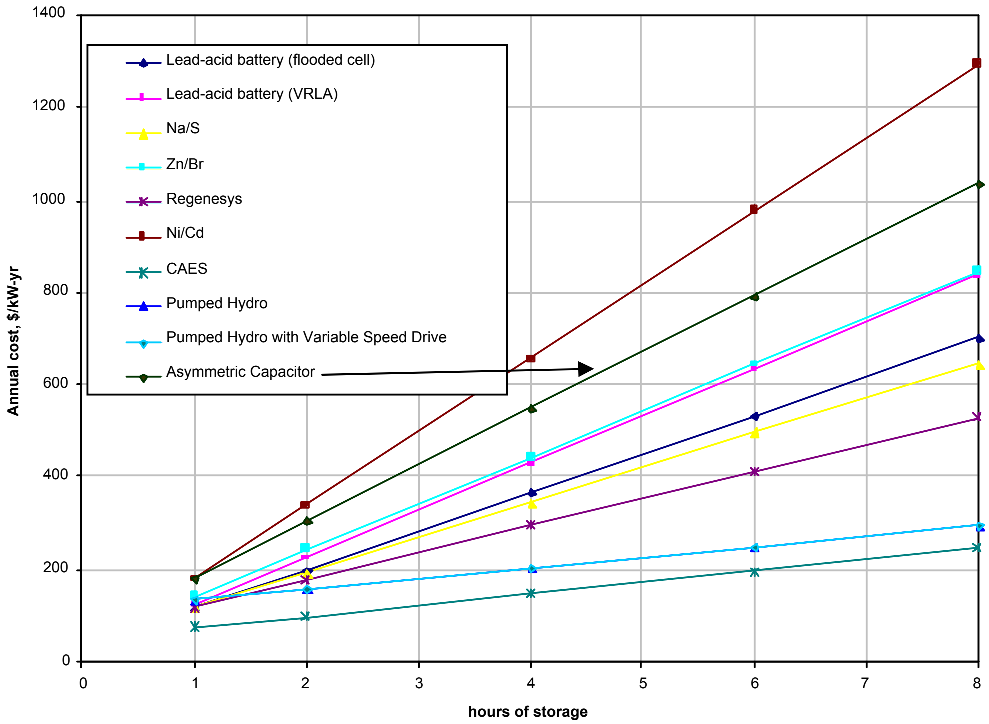


Figure 7. Levelized Annual Cost for Bulk Energy Storage Technologies. The Asymmetric Lead-Carbon Capacitor Cost Line is Marked by an Arrow.

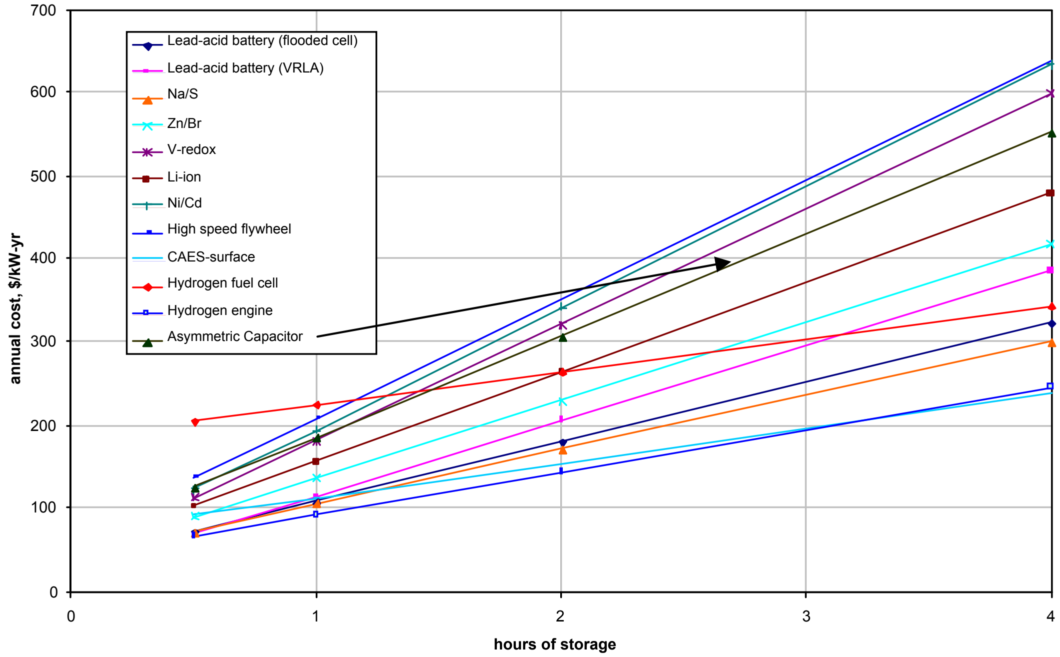


Figure 8. Levelized Annual Cost for Distributed Generation Technologies. The Asymmetric Lead-Carbon Cost Line is Marked by an Arrow.

4 Sensitivity Studies

In the previous report [1], results were calculated based on the parameters listed in Table 3. Some questions were raised about the sensitivity of the results to the assumptions for some of the costs and other parameters. In this current study, the values of some costs were varied to explore the sensitivity of the results. Also, the expected system life was varied for both the DG and PQ technologies. The original assumption of a 20-year life was based on the expectation that utilities would purchase these systems. Investments in these technologies might more likely be by commercial or industrial entities who do not anticipate such a long life. Also, benefits have more typically been calculated over a shorter life.[3] Therefore, shorter system life assumptions have been investigated. This impacts both the replacement period and the capital carrying charge rate, since the investment must be paid for over a shorter time period.

4.1 Selected Sensitivities

Table 6 indicates the sensitivities included in this analysis. All other assumptions remain the same as in the original study, here called the base case. The costs of consumables, electricity and natural gas, were varied to both a higher and lower value. The cost of natural gas directly affects only the CAES and surface CAES systems. It could impact electricity costs as well, but this was not calculated. Only shorter life times were considered, as discussed above. The carrying charge rate varies with system life, even for the same discount rate, as indicated in Table 6.

Table 6. Sensitivity Analysis Parameters.

Parameter	Base	Low	High
Charging Electricity, c/kWh	5	2.5	10
Natural gas (for CAES), $/MBTU	5	3.5	7
DG System life (levelization period), years	20	10	-
PQ System life (levelization period), years	20	5	10
Discount rate, %	8.5	-	-
For discount rate of 8.5%, life in years	5	10	20
Carrying charge rate, %	25.4	15.2	10.6

4.2 Electricity Cost Results

The sensitivity analysis for electricity costs used a wide range of prices, from halving to doubling the costs. However, as electricity cost is only a portion of the total annual cost, the overall costs are only particularly sensitive for the less efficient technologies. The results of varying electricity cost for 8-hr bulk storage technologies and 4-hr DG technologies are shown in Figures 9 and 10, respectively.

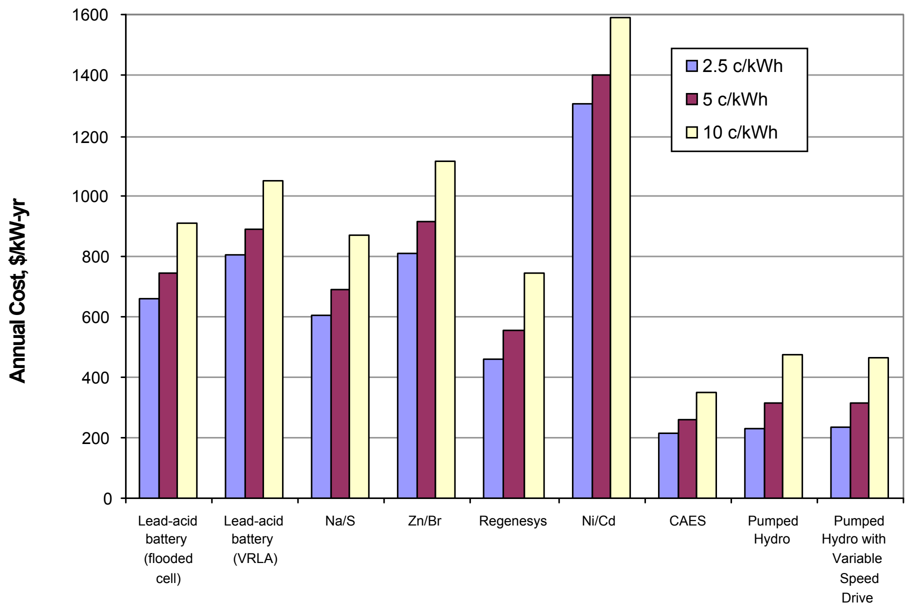


Figure 9. Sensitivity of Annual Costs to Electricity Costs for 8-hr Bulk Energy Storage Technologies.

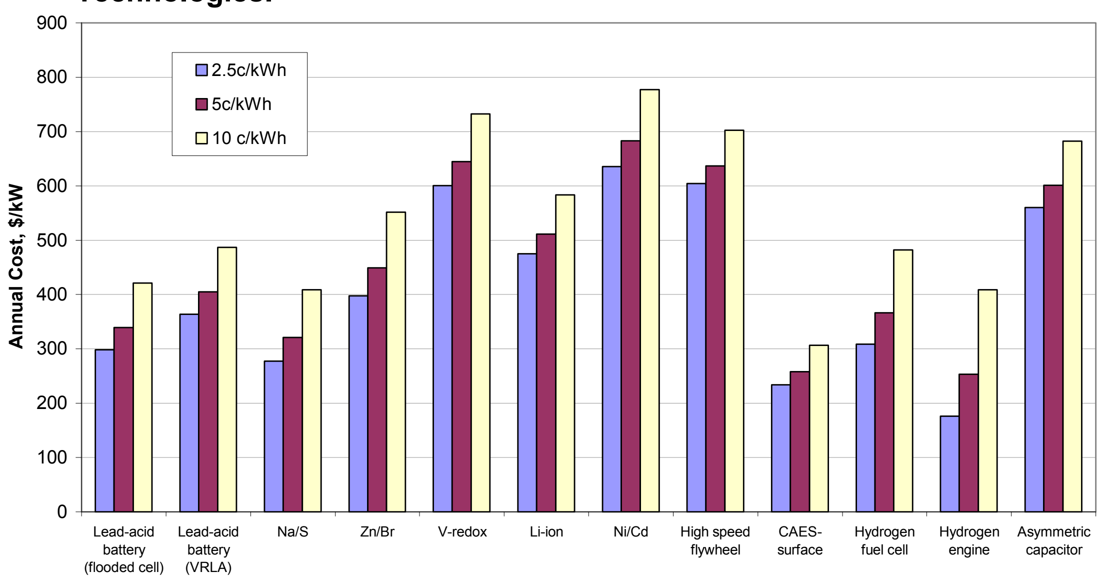


Figure 10. Sensitivity of Annual Costs to Electricity Costs for 4-hr Distributed Generation Technologies.

4.3 Natural Gas Cost Results

Sensitivity to the cost of natural gas is only relevant to the two technologies that consume natural gas directly, i.e., CAES and surface CAES. The impact on total annual cost for these two cases is shown in Figures 11 and 12, respectively. The base case is $5/MBTU. Increasing or decreasing this value impacts the fuel component, but because it is only a portion of the overall cost, it does not have a large overall impact.

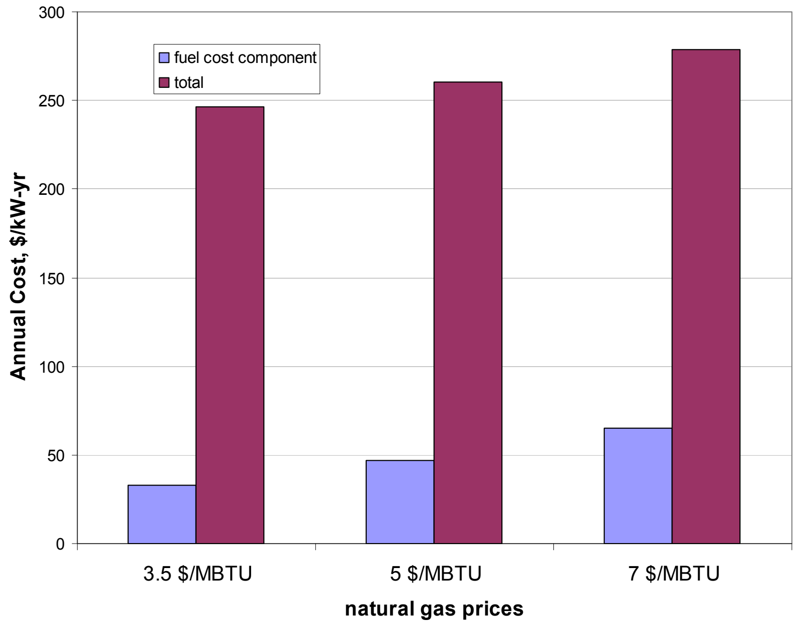


Figure 11. Sensitivity of CAES Annual Cost to Natural Gas Cost for an 8-hr System.

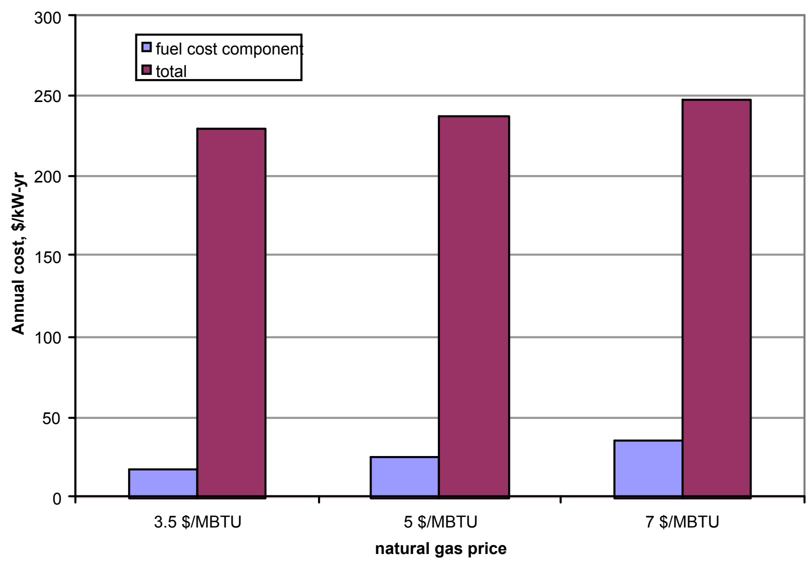


Figure 12. Sensitivity of Surface CAES Annual Cost to Natural Gas Cost for a 4-hr System.

4.4 Years of Life Results

As indicated previously, new calculations of annual cost were carried out using shorter expected system lives than the original study for distributed generation and power quality technologies. No new calculations were done for bulk storage systems, which were assumed to be installed by utility companies expecting 20-year life. For the DG technologies, a 10-year life is compared with a 20-year life. For the PQ technologies, both a 10-year life and a 5-year life are compared with the base case 20-year life.

The system life value has two effects on annual cost. The first is to increase the carrying charge rate because the system has to be paid for over a shorter time. This impact is pretty dramatic for all technologies. The second is to reduce or eliminate replacement costs, which counters the effect of the carrying charge. This impacts only those technologies with frequent and/or expensive replacement costs.

4.4.1 Effect on DG Technologies

Figure 13 shows total annual costs for 4-hr DG technologies comparing 10- and 20-year system life expectations. In general, nearly all the technologies have a higher annual cost with a 10-year life because of the higher carrying charge. This is particularly true for technologies that have high capital cost to begin with. In Figure 13, these would include the high speed flywheel, the hydrogen fuel cell and the asymmetric capacitor.

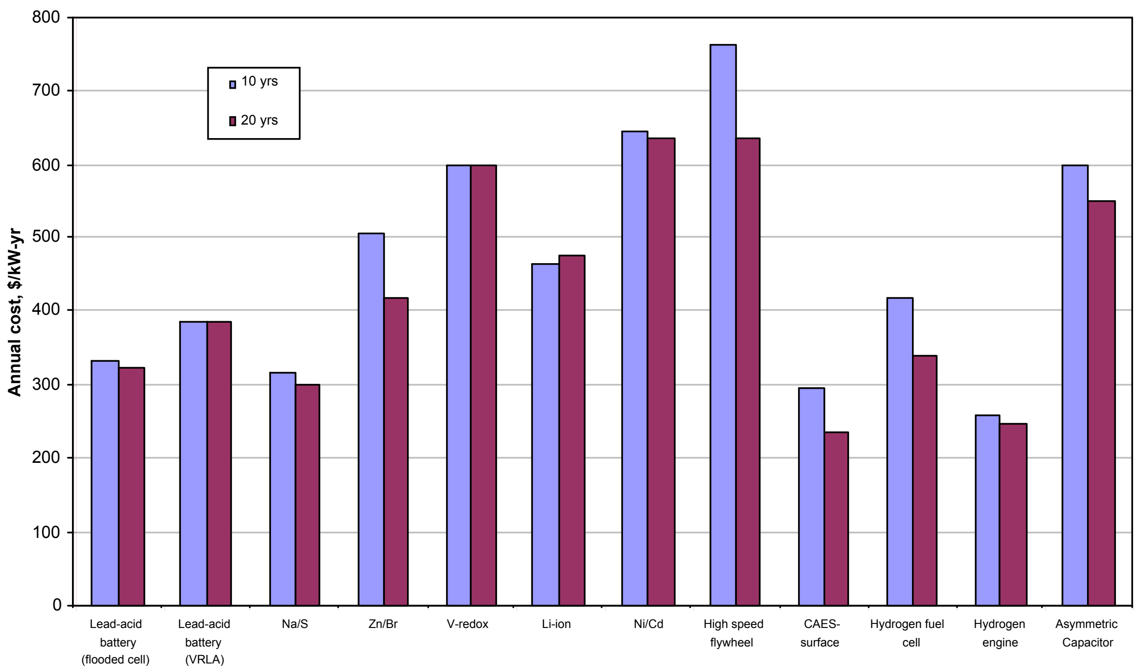


Figure 13. Sensitivity of Annual Cost to System Life for 4-hr Distributed Generation Energy Storage Technologies.

When comparing the components of cost for 10-year systems in Figure 14 with those presented earlier in Figure 3 for 20-year systems, it is possible to see the varying contributions of capital carrying charge and replacement costs. The high speed flywheel has very high capital component even though it has no replacement in either case.

A specific set of results for the lead-acid battery, VRLA battery and asymmetric capacitor is presented in Figure 15. This illustrates how even though the replacement costs are reduced, the increase in capital carrying charges offsets that advantage.

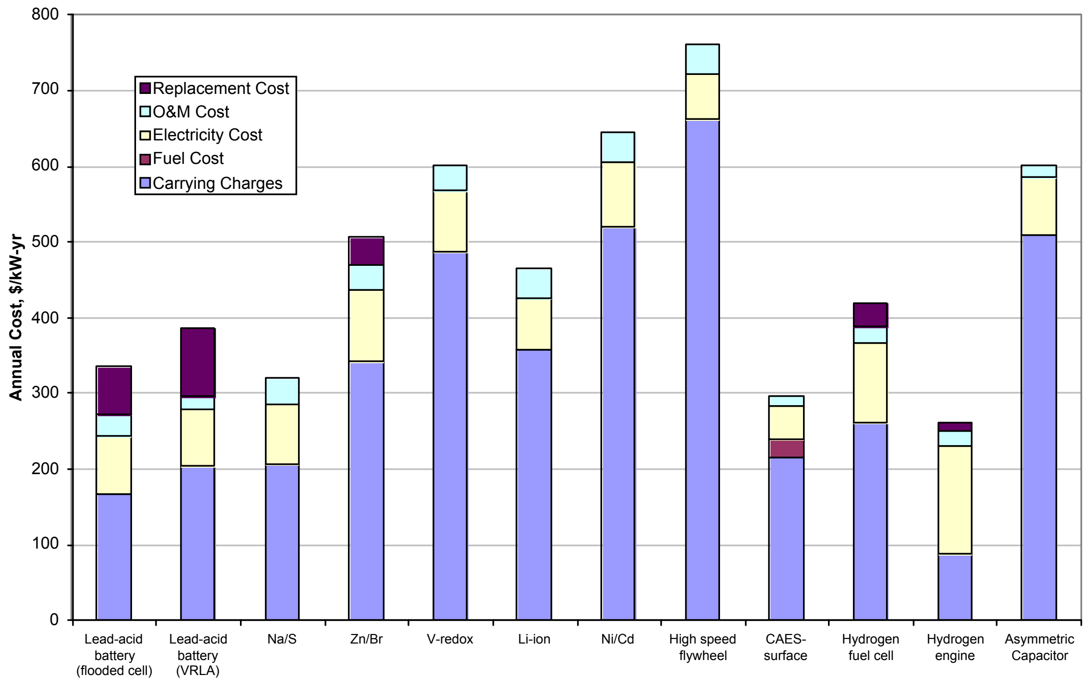


Figure 14. Annual Cost Components for 4-hr Distributed Generation Technologies (10-year Life).

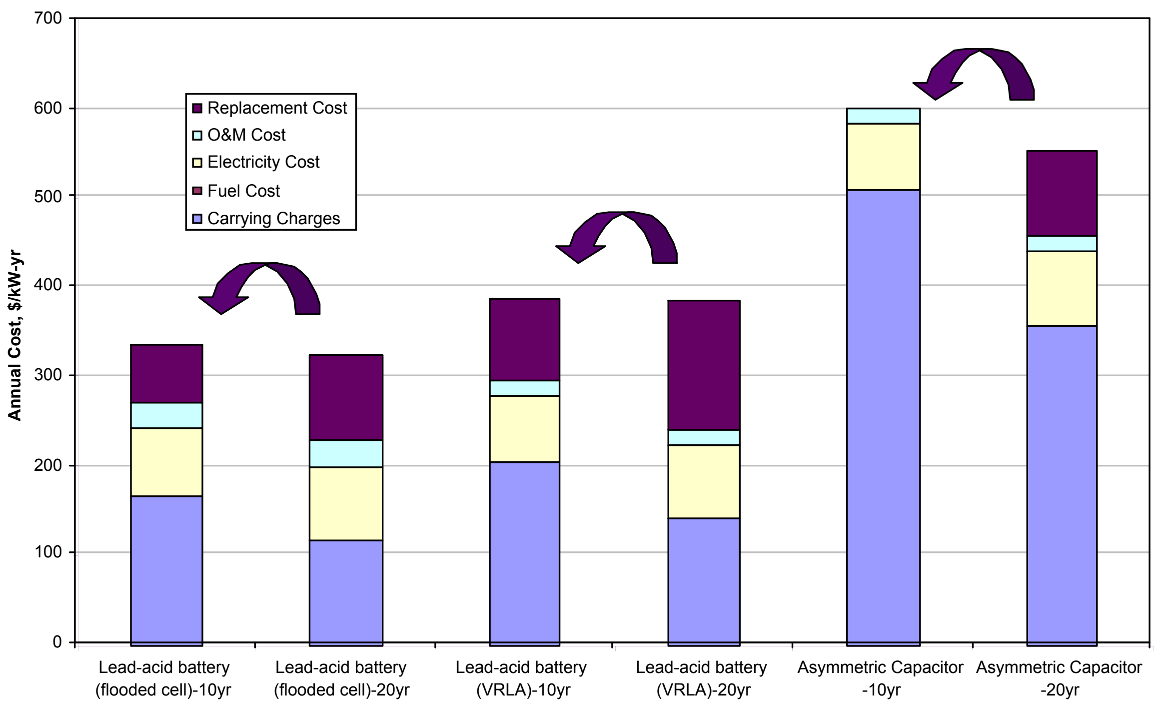


Figure 15. Annual Cost Components for Selected 4-hr Distributed Generation Technologies, Comparing 10- and 20-year Life.

4.4.2 Effect on Power Quality Technologies

Results for power quality technologies are shown in Figures 16 and 17 for 5-year, 10-year, and 20-year systems. Figure 16 is for 1-sec PQ systems and Figure 17 is for 20-sec PQ systems. The carrying charge rates for 5-yr, 10-yr, and 20-yr systems are 25%, 15%, and 10%, respectively. Again, the shorter the expected system life, the greater the annual cost. Since capital costs dominate for these systems, the increase is entirely due to the increased capital carrying charge. This is particularly true for the high speed flywheel (1).

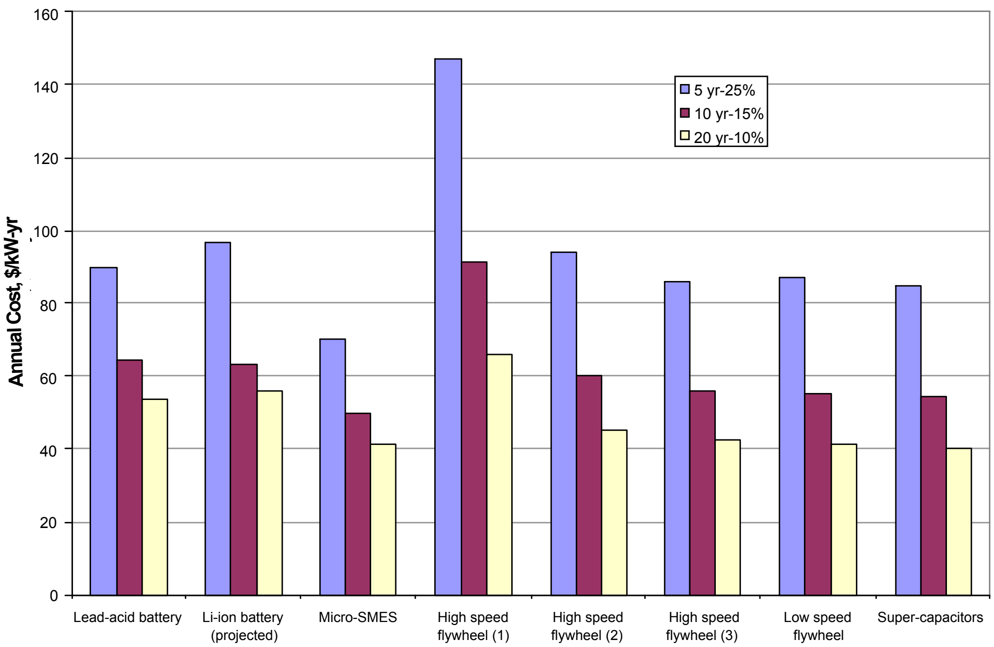


Figure 16. Sensitivity of Annual Cost to System Life for 1-second Power Quality Technologies. The Carrying Charge Rates for 5-yr, 10-yr, and 20-yr Systems are 25%, 15%, and 10%, Respectively.

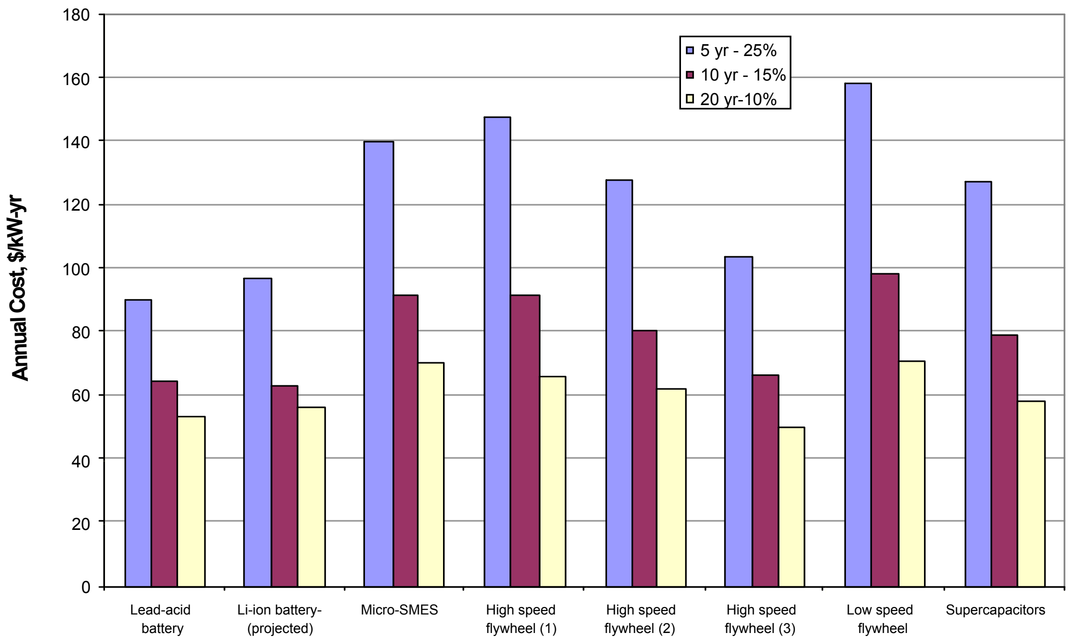


Figure 17. Sensitivity of Annual Cost to System Life for 20-second Power Quality Technologies. The Carrying Charge Rates for 5-yr, 10-yr, and 20-yr Systems are 25%, 15%, and 10%, Respectively.

5 Conclusions and Recommendations

Some conclusions from this and the previous studies include:

- Life-cycle cost analysis provides critical information that is not available from capital cost analyses alone, especially for distributed generation and bulk energy storage systems.
- Power quality system costs are dominated by capital cost and very sensitive to system life, mostly due to capital carrying charges.
- At current prices, lead-carbon capacitors compare with some of the more expensive technologies for both bulk storage and distributed generation applications. If projected large-scale production prices are achieved, they will be comparable with some of the least expensive technologies.
- All technologies show some sensitivity to electricity prices, especially those with the lower efficiencies.
- As assessed in the study, natural gas prices affect only CAES systems, but might also be reflected in electricity prices for the other technologies.
- System life assumptions significantly impact the annual capital carrying cost.
- System life also significantly impacts the need for component replacement and the associated costs.
- The savings in replacement cost are generally offset by the additional annual carrying cost, however, so the overall technology cost comparison is only modestly affected. Technology selection should be based on the system life desired by the user.

Recommendations for additional analysis include:

- Updating technology performance and cost data—based on the latest information.
- Compare costs and benefits in a consistent manner.
- Update graphical information available to the public, such as that on the Electricity Storage Association website.
- Add an application category that addresses a typical UPS function - a discharge duration of 30 seconds to 15 minutes.

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7. US Patent 6,466,429, “Electronic double layer capacitor”, Volfkovich et al., 10/15/02; US Patent 6,426,862, “Capacitor with dual electric layer”, Vosechkin et al., 7/30/02; US Patent 6,222,723, “Asymmetric electrochemical capacitor and method of making”, Razoumov et al., 4/24/01; US Patent 6,195,252, “Capacitor with dual electric layer”, Belyakov et al., 2/27/01.

Appendix A: Asymmetric Lead-Carbon Capacitor Analysis

Introduction

One type of asymmetric capacitor under development today is based on the use of lead-acid battery components as the positive electrode and a carbon-based capacitive component as the negative electrode. In this report, this combination is referred to as an "asymmetric capacitor", even though there are other devices that combine electrochemical and capacitive technologies. This asymmetric capacitor technology is projected to have two valuable attributes *vis-à-vis* electric utility applications. The first is a cycle life that may exceed 5000 diurnal, full[1] charge and discharge cycles. The second is a relatively low cost compared to other capacitors. The potentially lower cost is related to its utilization of some lead-acid battery fabrication technology. The combination of these two attributes has formed the rationale for support of the further development of this technology and it has been suggested that the asymmetric capacitor's life-cycle cost may be competitive with other electricity storage technologies. In the present analysis, we address only the use of the asymmetric capacitor for multi-hour storage. However, based on the performance of other capacitors, it is likely that devices of this type will also have high power capabilities that, if used effectively, will be of value to the owner.

Note: this assessment is based on a limited set of information that was available to the authors of this report. This information reflects some of the initial studies of this technology and was used in making assumptions to determine possible performance and system costs. Specifically, the following information is included

- Operating voltage limits 1.0 to 2.4 V
- Target cell energy capacity 0.14 to 0.20 kWh
- Energy density of test battery 0.023 Wh/cm^3
- Specific energy of test battery 12.8 Wh/kg
- Full discharge cycle life target >5000

The data presented to the authors have been screened for technical correctness and the system analysis is solely that of the authors of this report. Capacitor test data were not made available to the authors. For example, we have no data to support the concept of a lifetime for deep discharge exceeding 1000 cycles, nor is it confirmed that cell voltage will in fact vary over the range of 1.0 to 2.4 V in practical applications. Testing some cells at an accelerated rate will be needed once a design is fixed. Note, however, that actual confirmation of 5000 deep discharge cycles in this type of device would require multiple years of continuous operation. Thus, there are several estimates and assumptions involved in extrapolating to the characteristics and performance given above for the asymmetric capacitor.

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[1] Note: full or deep discharge refers to the nameplate rating of the cells, which will be determined by the capacity of the carbon-based, negative electrode. Only a limited fraction of material at the positive electrode participates even during the deepest cycle.

Finally, there are four U.S. patents that relate to this technology: 6,222,723; 6,195,252; 6,426,862; and 6,466,429. It is suggested in these documents that achieving a large number of cycles will require an excess of lead in the positive electrode, so that its mass will be at least 3 times what is required by the charge exchange at the negative electrode. This information has been confirmed by several conversations with capacitor experts. It has been observed by battery scientists that this level of excess material would also lead to increased longevity in a lead-acid battery. However, in this case, both positive and negative plates would require the larger quantity of lead.

The cost estimate given below will be used to compare the costs of the asymmetric capacitor to the costs of other energy storage technologies. Cost estimates for those technologies were carried out two or more years ago. In the meantime, the costs of many metals (lead in particular) have increased considerably faster than inflation. Since some fraction of the cost of the asymmetric capacitor is related to the costs of conventional lead-acid batteries, their per-unit of stored energy ($/kWh) costs used in previous analyses are used here as the basis for the asymmetric capacitor costs, rather than establishing new base costs. This approach would be desirable at some point, but would require an update and a full analysis of all technologies.

Since this asymmetric capacitor will be used solely for long-term storage, i.e., charge and discharge times will be several hours, it is further assumed that on this time scale, the electrolyte within the cell can diffuse without issues of concentration variations, heating, etc. and the resultant impact on internal electrical resistance and overall efficiency is minimal.

Asymmetric Capacitor Electrochemistry

The asymmetric capacitor evaluated here is based in part on the lead-acid battery. However, whereas the lead-acid battery has electrochemical reactions at the positive and negative electrodes, this capacitor only has such a reaction at the positive electrode. The negative electrode, which is essentially activated carbon, has a surface charge that changes with electricity storage level. This can best be understood by looking at the changes at the two electrodes during charge and discharge.

Asymmetric Capacitor Charging and Discharging

We first turn our attention to charging. During charge of any battery or capacitor, an externally applied voltage causes current to flow from the negative electrode to the positive electrode. Electrons, e^-, however, flow in the opposite direction, i.e., from the positive electrode to the negative electrode. In a pure capacitor, the removal of electrons from the positive electrode causes it to become more positive and the simultaneous increase of electrons in the negative electrode causes it to become more negative. In the asymmetric capacitor, the number of electrons at the negative electrode increases just as in a conventional capacitor; however, an electrochemical reaction occurs at the positive electrode.

Because the positive electrode of the asymmetric capacitor is the same as that used in a lead-acid battery, we can start with that component as an example. It will also help us later to recognize this similarity when estimating production methods and costs. Removing electrons from the positive electrode (charging), as shown in the first equation below, induces an electrochemical reaction. Lead sulfate and water are converted to lead oxide and sulfuric acid. In addition, protons, H^+, are released and enter the electrolyte.

$$PbSO_4 + 2H_2O - 2e^- \rightarrow PbO_2 + H_2SO_4 + 2H^+ \quad \text{Charge reaction at positive electrode}$$

or, as generally written by electrochemists,

$$PbSO_4 + 2H_2O \rightarrow PbO_2 + H_2SO_4 + 2H^+ + 2e^- \quad \text{Charge reaction at positive electrode}$$

Note that this combination of materials establishes a potential at the positive electrode of 1.69 V vs. the standard hydrogen electrode. This voltage is referred to as the reduction potential and is relatively stable so long as lead sulfate, lead oxide, and sulfuric acid are in contact. In particular, it depends on the concentration of sulfuric acid and other species and temperature as described by the Nernst equation. The reaction at the negative electrode of a lead-acid battery during charging involves the conversion of lead sulfate to lead. The reduction potential of the negative electrode of the lead-acid cell is about -0.36 V, which leads to the open circuit potential of a lead-acid cell of about 2.05 V.

The lead-based positive electrode of the asymmetric capacitor undergoes the same electrochemical reaction during charging as in the lead-acid cell. The negative electrode, however, is very different. The functional material is carbon, which, so long as the voltage is not excessive, does not participate in any electrochemical reactions. Perhaps the best way to visualize the effects of charging on the carbon-based negative electrode is to consider initially the state where it has no net electrical charge at the portion of its surface that is contact with the electrolyte. When a charging current is made to flow through the external circuit, the electrons removed from the positive electrode enter the carbon of the negative electrode, making it electro-negative. Though the exact form of the positive ions in the electrolyte adjacent to the carbon is an issue yet to be resolved, it can be imagined that this potential attracts H^+ in the electrolyte and a layer of these positive charges face a layer of negative charges on the surface of the carbon. This is referred to as the “double-layer”. The most important characteristic of this layer for electricity storage is its very small dimension, which results in a large capacitance. In addition, as the charge builds up, the attraction between the positive and negative charge layers may cause their separation to decrease, which increases the capacitance even more.

The above process is reversed at the negative electrode during discharge. Initially, as current flows through an external load, the voltage across the double layer decreases until all charge is removed from the negative electrode.

The reaction during discharge at the positive electrode can be expressed as:

$$PbO_2 + H_2SO_4 + 2e^- + 2H^+ \rightarrow PbSO_4 + 2H_2O$$

As discharge continues the double layer at the negative electrode reverses in character. The external potential at which this occurs will depend on construction and fabrication details and the rate of discharge. However, for low discharge rates, where internal resistive effects are minimal, this occurs at about 1.69 V. Electrons are removed from the carbon and it becomes positive, attracting negative ions to form a second type of double layer. The allowable voltage across this double layer is limited to avoid the decomposition of water and the evolution of gas. The species of ion on the double layer facing the carbon is not completely known at this time. It is clear that some large complexes and possibly hydrated compounds are involved, but definitive studies of the processes at the negative have not yet been carried out.

Asymmetric Capacitor Electricity Storage Capability

The asymmetric capacitor has three distinct parts that can limit its energy storage capacity. The first is the mass of the positive electrode, the second is the quantity of sulfuric acid, and the third has to do with the total capacitance (which is related to the total surface area) of the carbon components at the negative electrode.

As mentioned above, based on patent literature and expert opinion, it is assumed that the positive electrode must have about 3 - 4 times as much lead oxide as a typical lead-acid battery. Part of reason for this increase is the lower average cell voltage in the asymmetric capacitor as compared to the lead-acid battery voltage. This difference means that 20 to 30 % more ampere-hours are needed to deliver a given quantity of stored electricity.

The quantity of sulfuric acid in the asymmetric capacitor also affects energy storage capacity. During discharge, sulfuric acid and lead oxide are converted to lead sulfate at the positive electrode. Thus, the quantity of sulfuric acid needed for this purpose is proportional to the amount of lead oxide transformed in the maximum discharge cycle. Sulfuric acid also reacts at the negative electrode of a lead-acid battery, while there is no reaction in the asymmetric capacitor. As a result, there should be about 60% as much sulfuric acid in the asymmetric capacitor as in a lead-acid battery storing the same amount of energy. The electrolyte in both the battery and the capacitor must maintain conductivity and reactivity at the end of discharge, i.e., some of the sulfuric acid must remain unreacted to accommodate this requirement.

It appears that the two most critical issues for the carbon negative electrode are: 1) assuring adequate electrical conductivity between the negative terminal and the carbon that is in contact with the electrolyte, and 2) assuring the absence of electrochemical action at any location within the negative electrode. Many details of collector design, coatings, carbon selection, and fabrication must be addressed to assure these conditions are met over the 5000-cycle target life of the capacitor. We assume these issues can be resolved eventually and it is possible that other design changes to the negative electrode will improve overall performance.

A variety of carbon materials can be used for the negative electrode. One possibility is to have a mat made of activated carbon fibers that supports a mass of activated carbon particles. Both materials have been characterized with respect to capacitance, surface area, and energy storage capacity, and are available commercially in several grades. The quality must be chosen to assure absence of contaminants that could react with the electrolyte. The price of activated carbon depends on purity and other characteristics, and the range in cost today is roughly from 2 to 200 $/kg. The cost of activated carbon for some high-power-density capacitors today is at the upper end of this range. Some canister applications, where tons of material is needed per year, use activated carbon at the lowest end of the range. The question to be answered is "what will the carbon in the asymmetric capacitor cost?"

Today, high purity activated carbon materials with these characteristics cost about 30 $/kg in modest quantities. It is expected that the cost will come down to somewhere between 5 and 15 $/kg in the event of large-scale production of asymmetric capacitors.

This type of material can store about 100 Wh/kg of activated carbon, or 20 Wh/kg of carbon and absorbed electrolyte, which is consistent with the characteristics of an existing 7-cell model asymmetric capacitor that stores 1 kWh and weighs about 80 kg. We estimate the carbon weight to be 14 kg. If we take the cost of high quality carbon as 28 $/kg, the carbon electrode cost would be about 400 $/kWh. The long-term cost of this component may be as low as 100 $/kWh at 7 $/kg for the carbon. (Note: there are hopes that less expensive carbon could be used, but this is uncertain.)

The volume of the carbon-based negative electrode and the collector plate is considerably larger than the volume of the lead-acid battery equivalent. Without detailed information on the devices, it is not possible to come up with exact sizes. However, it appears that the energy density of the active material will be about 60 Wh/liter of combined electrolyte and carbon.

Asymmetric Capacitor Cost

Several approaches can be used to estimate the cost of the asymmetric capacitor. Here, we base the estimate on a combination of present day, conventional lead-acid battery costs, the costs of the carbon-based materials, the special fabrication costs, and the containment costs. In previous comparisons the lead–acid battery cost was estimated to be between 150 and 200 $/kWh, depending on the type in use. Since the asymmetric capacitor has many of the same components, we use this as a starting point and adjust for differences in materials and fabrication requirements. The following cost development is based on discussion with a battery and capacitor expert.[2]

For this estimate, the "as delivered" lead-acid batteries capital cost is divided among the following: positive electrode, negative electrode, case, separators, and electrolyte in the percentages as listed below. Costs for marketing, development, etc., are distributed among the various physical components. The cost figures are based on 150 $/kWh for the batteries.

Positive electrode	30 %	$45
Negative electrode	30 %	$45
Electrolyte	15 %	$22.5
Separator	10 %	$15
Case/Containment	15 %	$22.5
Total for lead-acid battery	**100 %**	**$150/kWh**

[2] Hassenzahl personal discussions with Phil Symons of Electrochemical Engineering Consultants, Inc.

Based on these costs and the above assessment of the asymmetric capacitor material requirements, we can estimate today's costs for the lead-carbon asymmetric capacitor.

Positive electrode	$155	Approximately 3.5 times cost in lead-acid battery
Negative electrode	$400	Carbon and special materials for negative electrode and fabrication.
Electrolyte	$15	Approximately 60 % of cost in lead-acid battery
Separator	$15	Assume the same as lead-acid battery
Case/Containment	$40	Lead-acid plus reinforcement to maintain conductivity

Total for lead-carbon capacitor 625 $/kWh

What will happen to the cost if many units are fabricated? We assume that only the negative electrode will be affected because the low cost of lead-acid batteries in large scale production are used for the other cost elements.

Positive electrode	$155	Approximately 3.5 times cost in lead-acid battery
Negative electrode	$100	Mass produced carbon and special materials for negative electrode and fabrication.
Electrolyte	$15	Approximately 60 % of cost lead-acid batteries
Separator	$15	Assume the same as lead-acid battery
Case/Containment	$40	Lead acid plus reinforcement to maintain conductivity
Total for future capacitor	**325 $/kWh**	

Asymmetric Capacitor Performance and Other Considerations

There are several issues associated with performance of any energy storage system that must also be evaluated for the asymmetric capacitor. These include efficiency, cycle life, power conversion equipment, maintenance, safety, etc. Some of these cannot be determined with certainty at this time. Only operational experience with hundreds of units will allow good prediction of these quantities. However, to make comparisons with other technologies, it is necessary that they be addressed at some level.

The efficiency of an asymmetric capacitor depends on a variety of factors. Some test data showing charge and discharge voltages and currents would be of value but were not available at the time this document was prepared. Nevertheless, there is reason to believe that the efficiency will be slightly better than that of a conventional lead-acid battery. In an earlier report, the authors estimated that the efficiency of some supercapacitors for pulsed applications could be as high as 95%. Asymmetric capacitors will experience some of the losses of the lead-acid battery, but are expected to operate in the range of 80+% efficiency.

Extended cycle life has been shown for other types of capacitors, such as symmetric and asymmetric Ni-Carbon hydroxide systems. Some tests have shown that these asymmetric capacitors can operate for well over 5000 cycles with essentially no reduction in performance.

However, no evidence was presented to show that 5000 cycles had been achieved for the lead-carbon asymmetric capacitor.

In general, battery performance is rated at the end of life, which is about 80% of the as-constructed capacity. Since there is no relevant data, we have assumed the same is true for the asymmetric capacitor in the assessment of the material requirements and costs. This may prove to be inappropriate and some characteristics may have to be changed.

The voltage range for the asymmetric capacitor is assumed to be 1.0 to 2.4 V, which is larger than the voltage range of other energy storage technologies. Details of capacitance as a function of charge state and voltage were not discussed above. However, it is known that the capacitance of the system is dynamic and increases considerably with increasing charge level. Thus, the large voltage range is necessary to use the carbon in the most effective way. The implication is that the power conversion equipment for charge and discharge must operate over a wider voltage range. This increases PCS cost. In an earlier study, the costs of PCS systems for many electricity storage systems were presented. Because the comparison here has been between batteries and the asymmetric capacitors, we continue with that approach. The costs of the silicon power components are about 50 % of the overall converter cost and, for a fixed current, are roughly proportional to the voltage. Since power must be delivered at all charge levels, including the minimum and the maximum, the ratio of the highest to lowest voltage across the asymmetric capacitor, 2.4, determines that considerably more silicon is needed for the capacitor than for the battery. A more detailed study will be required for an exact calculation, but a conservative estimate of the cost of the asymmetric capacitor PCS is that it will be twice as much as for an equivalent battery.

Maintenance, safety and proper care of these capacitors will be somewhere between that of lead-acid batteries and supercapacitors. Under normal operation, it can be expected that after some initial tests the systems will function with minimal monitoring and limited (or no) maintenance for a life of 5000+ cycles. Utilities, based on past experience, will not accept “zero maintenance” as a characteristic of any system. Either the utility will provide personnel to address this issue on a regular basis or will establish a maintenance contract with the supplier. Thus, we apply an O&M estimate of 5 $/kW/yr (the same as for VRLA batteries).

Conclusions

Today, the asymmetric capacitor is in an experimental stage of development. Some devices have been constructed, mainly by scientists who understand the details of the system and what is needed to make them work correctly and thus can correct any defects during assembly. Though proponents claim that the technology is based on the lead-acid battery, only the positive electrode is typical of this existing technology. Eventually, as more and more systems are constructed and the technology approaches the prototype stage, it will be necessary to move the fabrication of the negative electrode and the assembly of the entire system into a commercial status. At that time, it will be appropriate to reassess system costs. It is not known if any of the existing cells of this type of asymmetric capacitor have achieved 5000 cycles. It is important to explore this issue early in the next stage of research.

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