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Energy Storage Systems Cost Update

A Study for the DOE Energy Storage Systems Program

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Abstract

This paper reports the methodology for calculating present worth of system and operating costs for a number of energy storage technologies for representative electric utility applications. The values are an update from earlier reports, categorized by application use parameters.

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Introduction and Background

This work presents an update of energy storage system costs assessed previously and separately by the U.S. Department of Energy (DOE) Energy Storage Systems Program. The primary objective of the series of studies [1,2,4,5,6] has been to express electricity storage benefits and costs using consistent assumptions, so that helpful benefit/cost comparisons can be made.

The framework for benefits and cost analysis was developed under a number of earlier studies sponsored by the Program, most specifically the study *Benefit/Cost Framework for Evaluating Modular Energy Storage* by Distributed Utility Associates and Longitude 122 West, Inc. [1], which establishes consistent bases and assumptions used to calculate the costs and benefits of energy storage. The most important factors influencing total life-cycle cost are the capital cost of the equipment, followed by replacement costs (if any), and, finally, the cost of energy for recharging. Replacement costs are affected by expected service life and the life-cycle costs of energy (based on system efficiency). Benefits, in large part, depend on the functions required by the user and, again, the expected service life of the system. When calculating the benefits or costs of a storage system over the entire life of the system, proprietary information and algorithms are sometimes used to calculate a value that is then multiplied by the present worth factor to determine the present worth of the cost or benefit. Service life, discount rate, and inflation rate are three factors used to calculate the 'present worth' factor, which provides a simple, consistent way to represent the value of a regular stream of revenues or payments for a given number of years (ten in this case). Other foundational work includes that described in [2] and [3]. Costs and methodology are updated from work by Longitude 122 West and Advanced Energy Analysis [4, 5, 6].

The 'present worth' concept is used so that the cost numbers provided here are directly comparable to the quantified benefits published elsewhere by the Energy Storage Systems Program. Normalized system cost ($/kW) is one of the most important factors for stationary applications. System cost depends on many factors and includes all ancillary equipment necessary for the full storage system. While capital cost is important, total ownership cost, including operations & maintenance (O&M) costs, is a much more meaningful index for a complete economic analysis. In general, present worth is based on ownership of the device over 10 years for a given application and includes the following factors:

- Efficiency
- Cycle Life
- Initial Capital Costs
- Operations and Maintenance
- Storage-device Replacement

Thus the present worth (or present value) calculation includes not only capital cost, but operating costs as well. The most important characteristics include round-trip electrical energy efficiency (kWh out/kWh in) and cycle life. Because cycle life, or number of discharges before replacement is required, is an important cost driver, the use of the system, as defined by the planned application, must be considered.

The Energy Storage Program always tries to use the most up-to-date cost and performance values; although they often change. In general, system cost and performance information is obtained from reports published by the Electric Power Research Institute (EPRI); information provided by certain utility partners; and from the results of DOE-sponsored research projects and field demonstrations. The latest sources of data for this brief report can be found in References [7, 8, 9, 10] and also in internal Program documents [11].

These results are also being presented in background material on the Electricity Storage Association website. [12]

Technologies and Application Categories

Frequency and Duration Characteristics

As discussed above, the frequency of operation (and thus planned discharge cycles) is an important parameter for calculating life-cycle cost or present worth of life-cycle cost. The applications for energy storage can be roughly categorized by whether frequent cycling is expected, as in daily load-leveling, or infrequent discharge is expected, as in capacity applications.

Likewise, utility energy storage applications can be roughly categorized by whether a short capacity or discharge is needed (on the order of less than minutes) or whether a long storage or discharge time is expected (on the order of hours). Therefore, for this analysis, four utilization categories have been identified so that appropriate system costs could be evaluated. The four categories are defined in Table 1.

Representative applications or value propositions are also listed in Table 1. Many more applicable value propositions are defined and discussed in [14]. Most are covered by these general technology application categories.

Table 1. Operation/Use Categories

Category/Definition	Hours of Storage	Use/Duty Cycle	Representative Application
Long-duration storage, frequent discharge	4 – 8*	1 cycle/day × 250 days/year	Load-levelling, source-following, arbitage
Long-duration storage, infrequent discharge	4 – 8*	20 times/year	Capacity credit
Short-duration storage, frequent discharge	0.25 – 1**	4×15 minutes of cycling × 250 days/year = 1000 cycles/year***	Frequency or area regulation
Short-duration storage, infrequent discharge	0.25 – 1**	20 times/year	Power quality, momentary carry-over

* This analysis uses 4 hours unless otherwise noted

** This analysis uses 1 hour unless otherwise noted

*** Some technologies are capable and will be used up to 10,000 cycles/year

Technologies Considered

For this analysis, only the most common technology systems were evaluated. For the most part, these types of systems correspond to those analyzed in previous assessments. Costs have simply been updated using the previous methodology. The technologies and appropriate use categories are listed in Table 2. In some cases, the listed applications may be unrealistic; the cost calculations were performed for completeness. For example, flow batteries may not *practical* for applications needing only short-duration storage, but *could be used* in this way if necessary.

Table 2. Technologies Considered

Technology	Appropriate Use(s)
Advanced lead-acid batteries (2000 cycle life)	1, 2, 3, 4
Sodium/sulfur batteries	1, 2
Lead-acid batteries with carbon-enhanced electrodes	1, 2, 3, 4
Zinc/bromine batteries	1, 2, 3, 4
Vanadium redox batteries	1, 2, 3, 4
Lithium-ion batteries (large)	1, 2, 3, 4
Compressed air energy storage (CAES)	1
Pumped hydro	1
Flywheels (high-speed composite)	3, 4
Supercapacitors (double-layer electrochemical)	3, 4

The technologies considered include those described and considered previously [5], but several have seen some significant development in the past few years. In particular, Li-ion batteries are now available in many different chemistries; the most promising is considered here. Also, lead-acid batteries with carbon-enhanced electrodes are the latest variation on lead-carbon asymmetric batteries or capacitors.

Cost Calculations

This section of the report contains a description of the life-cycle cost analysis performed for this study. It follows the same procedure as that in [1], which results in the present worth of costs (capital and operating) for 10-year operation. (Note that although the term "life-cycle" sometimes refers to an analysis that includes the eventual disposal of the spent capital equipment, the disposal component is not included in this analysis.)

Cost Methodology

Energy storage system components are shown in Figure 1.

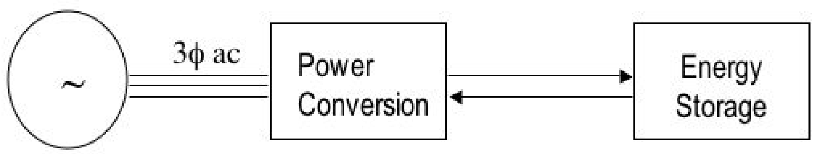

Figure 1. Major cost components of the energy storage system are the storage unit ($/kWh) and the power conversion unit ($/kW). The balance of plant is typically costed with the storage unit.

Capital Cost

The capital cost calculation, in its simplest form is—

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

The cost of the power conversion equipment is proportional to the power rating of the system:

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

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

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

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 or storage time.

All systems have some inefficiency. To account for this, Equation 3 is modified as follows—

$$\mathrm{Cost_{storage}}\ (\$) = \mathrm{UnitCost_{storage}}\ (\$/\mathrm{kWh}) \times (\mathrm{E}\ (\mathrm{kWh}) / \eta\ ) \tag{4}$$

where η is the efficiency.

Only when, the unit costs of the subsystems are known, and the storage capacity in kWh is known, it is possible to rewrite the capital cost in terms of the power rating:

$$Cost_{system}\ (\$/kW) = Cost_{total}\ (\$)\ /\ P\ (kW) \qquad (5)$$

Life-cycle Cost

The calculation of life-cycle cost includes the cost of capital, O&M, electricity for recharging, fuel (for CAES), and replacement costs. Life-cycle cost calculations are described in detail in [4].

Present Worth

Present worth, or present value, is the value on a given date (*e.g.*, the beginning of the project) of a future payment or series of future payments, discounted to reflect the time value of money. In this analysis, present worth *cost* is the sum of all discounted costs over the 10-year life of the system. A detailed rationale for the concept's use and examples of how it is used to calculate benefits *and* costs are provided in [1]. The same methodology has been used here to calculate the present worth (PW) factor of the life-cycle cost. The equation for the PW factor for a 10-year service life is as follows:

$$\text{PW factor} = \sum_{i=1}^{10} \frac{(1+e)^{i-.5}}{(1+d)^{i-.5}} \qquad (6)$$

e = annual price escalation rate (%/year)
d = discount rate (%/year)
i = year

This factor is combined with other values obtained using other information and algorithms (which are sometimes proprietary) to calculate the present value (or present worth) of a given cost (or benefit).

Economic Assumptions

Costs associated with storage system use are calculated in this study using the assumed financial values shown in Table 3. Most notable, in order of significance, are a) 10-year storage system service life, b) 10% discount rate, and c) 2% annual price escalation (inflation) rate. When the same values are assumed in the calculation of benefits, the two can be compared.

Table 3. Assumptions for Life-cycle Benefit and Cost Analysis

Parameter	Value
General Inflation Rate	2%
Discount Rate	10%
Service Life	10 years
Utility Fixed Charge Rate	11%
Customer Fixed Charge Rate	15%
Fuel Cost, Natural Gas (surface CAES only)	$5/MBTU
Electricity Cost, Charging	10¢/kWh

Cost and Performance Assumptions

Cost is calculated for a system by adding the cost of the storage unit and the power conditioning system. These subsystems are treated separately because they provide different functions and are priced by different ratings. Power components are priced in $/kW. Energy storage units are priced in $/kWh. For this reason, the individual subsystem costs are needed, although they are often difficult to separate from vendor system prices. The values used in this update are listed in Table 4, along with references.

The costs in Table 4 are based on certain standard assumptions for the applications and technologies considered, and on expert opinion. They are meant to be used for comparative purposes. The actual costs of any storage system depend on many factors and the assumptions and the means of calculating some of the values used are subjective and continue to be debated, even among experts in the field.

Table 4. Cost and Performance Assumptions

Technology	Power Subsystem Cost $/kW	Energy Storage Subsystem Cost $/kWh	Round-trip Efficiency %	Cycles	Source
Advanced Lead-acid Batteries (2000 cycle life)	400	330	80	2000	8
Sodium/sulfur Batteries	350	350	75	3000	8, 9, 10
Lead-acid Batteries with Carbon-enhanced Electrodes	400	330	75	20000	8, 10, 13
Zinc/bromine Batteries	400	400	70	3000	10
Vanadium Redox Batteries	400	600	65	5000	11
Lithium-ion Batteries (large)	400	600	85	4000	8,10
CAES	700	5	N/A (70)	25000	8
Pumped hydro	1200	75	85	25000	10
Flywheels (high speed composite)	600	1600	95	25000	10
Supercapacitors	500	10000	95	25000	12

Results and Observations

Results

The calculated values for present worth ($/kW) are listed in Table 5 and shown graphically in Figure 2.

Table 5. Present Worth Cost of 10-year Operation in Year 1 ($/kw)[1]

Technology/Use	Advanced Lead-acid Battery	Na/S (7.2 hr)	Zn/Br	V-redox	Lead-acid Battery with Carbon-enhanced Electrodes	Li-ion	CAES (8 hrs)	Pumped Hydro (8 hrs)	High-speed Flywheel (15 min)	Supercap (1 min)
Long-duration storage, frequent discharge	2839.26	2527.97	2518.03	3279.34	2017.87	2899.41	1470.10	2399.90		
Long-duration storage, infrequent discharge	1620.37	2438.97	1817.82	2701.41	1559.57	2442.79				
Short-duration storage, frequent discharge	1299.70		905.53	1459.85	669.85	1409.99			965.73	834.62
Short-duration storage, infrequent discharge	704.18		697.78	999.78	625.57	960.48			922.87	793.02

[1] Storage duration 4 hours, unless otherwise noted.

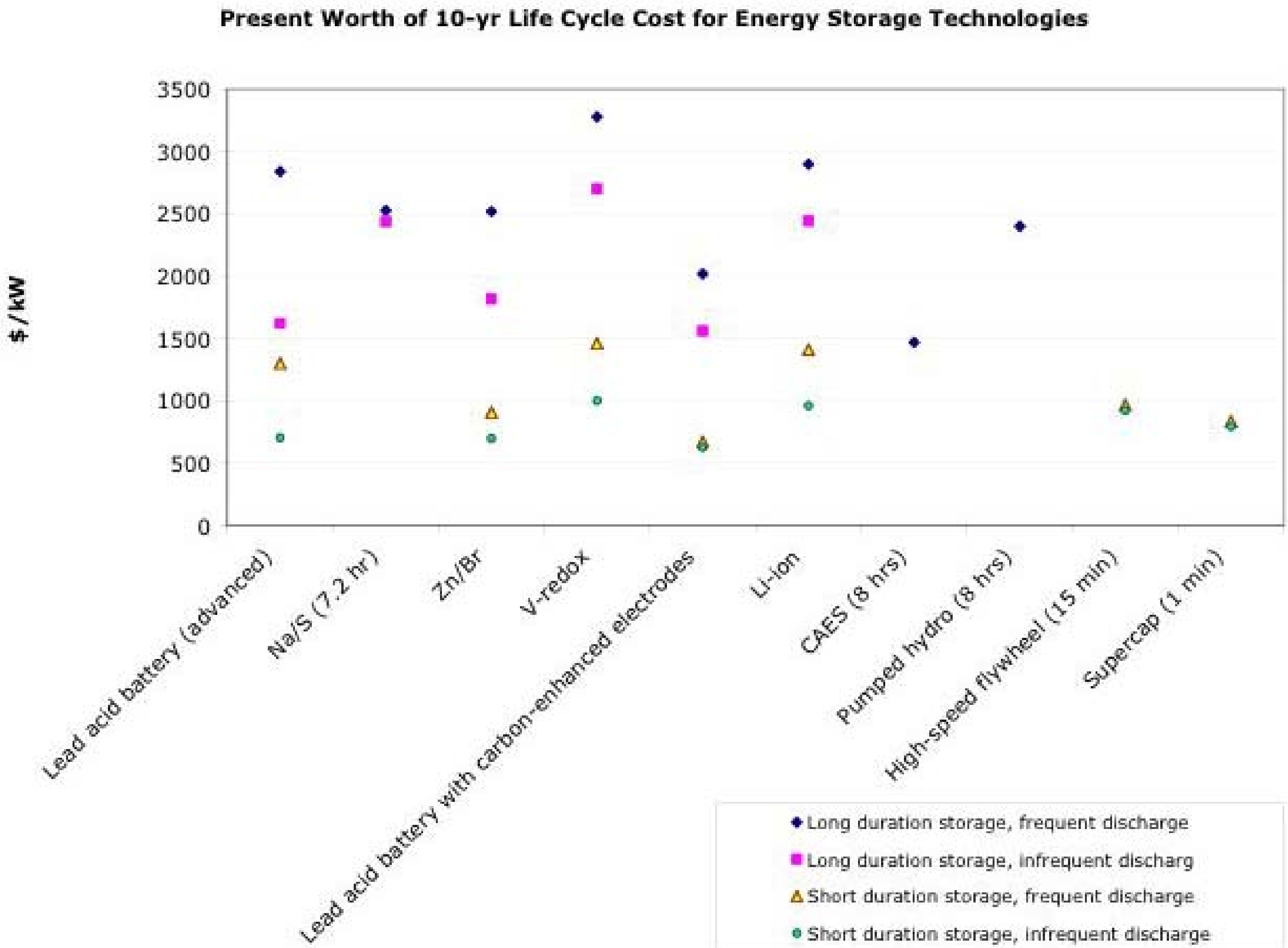

Figure 2. Graphic representation of 10-year present worth cost.

Observations

As seen in Figure 2, present worth is highly variable, not only between technologies, but also between application categories. The most obvious difference is between long-duration and short-duration uses; long-duration use simply requires more storage capacity. The least expensive long-duration storage is found for CAES, but this of course requires an appropriate geologic site.

The differences between frequent and infrequent operation are also substantial for some technologies. Frequent use is more expensive because more electricity is purchased for charging, and because some technologies will outlive their cycle life during the 10-year time frame and expensive replacements will be required. Technologies with good cycle life are more attractive for applications requiring frequent charge and discharge.

Summary

Costs of energy storage systems depend not only on the type of technology, but also on the planned operation and especially the hours of storage needed. Calculating the present worth of life-cycle costs makes it possible to compare benefit values estimated on the same basis.

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