

Life-Cycle Cost Analysis of Energy Storage Technologies for Long- and Short-Duration Applications

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Introduction

Applications of energy storage have a wide range of performance requirements. One important feature is discharge duration. This paper reports recent results based on a set of studies² to characterize energy storage technologies with a range of discharge capabilities. The overall goal is to provide a quantitative comparison of energy storage alternatives. As indicated in Figure 1, the first study compared technologies on the basis of a number of parameters, in particular capital cost. Technologies have been further evaluated on the basis of life-cycle costs, which are expressed in annual \$/kW. Current efforts are extending the analysis to examine sensitivity to various assumptions, including the cost of electricity. Although estimation of the benefits of electricity storage systems is critical to their implementation and use, that analysis is not included in this effort. The plan is to combine costs and benefits in future efforts, including an industry workshop.

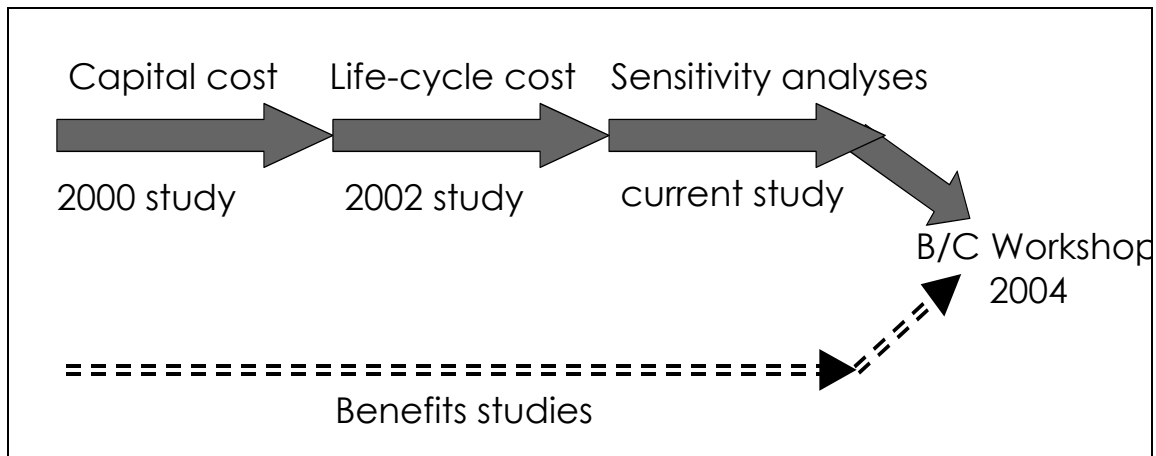


Figure 1. Progress of Comparative Studies of Energy Storage Technologies.

Scope of the Studies

The analysis of life-cycle costs has been performed for several application categories. These application categories include:

- bulk energy storage for large-scale load-leveling, with discharge duration up to 8 hrs;
- distributed generation (DG) systems for peak shaving, with discharge duration from 1 to 4 hours; and
- power quality / end-use systems with short duration discharge up to 30 seconds.

The technologies evaluated included: batteries (conventional and advanced), flywheels (low and high speed), supercapacitors, compressed air energy storage (CAES), superconducting magnetic energy storage (SMES), pumped hydro, and hydrogen, primarily for use in fuel cells. Earlier results based on capital cost and system sizing (power rating and storage capacity) have shown the importance of the hours of storage to the choice of most suitable technologies for a given application. [1,2]

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Life Cycle Cost Analysis

Life-cycle costs include not only the cost of capital, but also operation and maintenance (O&M), electricity and natural gas (for CAES), and replacement costs. The life cycle cost approach used in the current and the previous study is described in detail in Ref. [3]. Results are typically shown as annual cost in \$/kW-yr. A representative example – for DG systems sized to deliver energy for 4 hours per day – is shown in Figure 2. The components of the annual cost are indicated: capital carrying charge, electricity, natural gas (for surface CAES only), O&M, and replacement costs. The percentage shown in parentheses above each bar is the portion of the annual cost due to the capital carrying charge. Although the capital expense is always a major component, the fraction varies widely across the technologies. This result shows the importance of considering the full life-cycle cost when comparing technologies, not just capital cost. This result is true for all the applications studied, although less so for the power quality systems, where capital costs dominate.

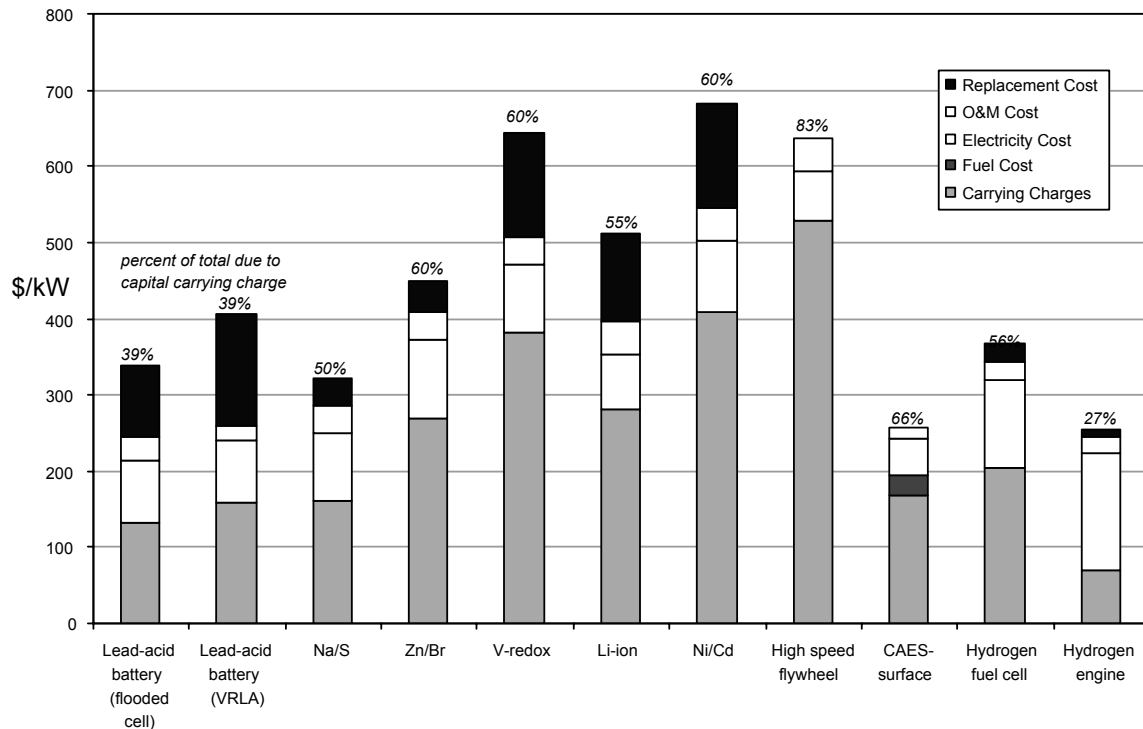


Figure 2. Components of Annual Cost (\$/kW-yr) for 4-hr DG Systems

Sensitivity Studies

Energy storage system costs (both capital and life-cycle) have been shown in previous work to be strongly dependent on the storage discharge time, or storage capacity. The results are also dependent on other assumptions, such as electricity price and replacement frequency and cost. The latter parameters depend in turn on the system life expectation. Therefore, sensitivity analysis is in progress in the current effort to determine how significant these and other assumptions are to the results and conclusions. The parameters of the sensitivity study are listed in Table 1.

Table 1

Parameter	Base	Low	High
Charging Electricity, ¢/kWh	5	2.5	10
Natural gas (for CAES), \$/MMBTU	5	3.5	7
DG System life (levelization period), years	20	10	
PQ System life (levelization period), years	20	10, 5	
Discount rate, %	8.5	5	10
		TBD	
Replacement costs	Base case	Review for each technology	
Replacement period	Base case	Review for each technology	
Shipping, taxes, import fees	none	Research for individual systems	

Sensitivity to Electricity Prices - Results

In the energy storage applications and systems considered here, electricity is used to recharge the system. For bulk energy storage systems, those designed for load-leveling applications, the assumption is made that this recharging activity will take place off-peak, so that relatively low-priced electricity is purchased. This assumption is also true for most distributed generation systems. They operate at most several hours per day, and can be easily scheduled for recharge off-peak. Only the hydrogen / electrolyzer systems are constrained to using day-time electricity because the electrolyzer is rated for continuous operation whenever the power system (fuel cell or engine) is not operating. This minimizes the capital cost of the electrolyzer. Power quality systems can also be recharged off-peak. Their parasitic, housekeeping needs must be met at all hours and this can sometimes be a higher power draw than recharging the system. These operational issues have been taken into account when calculating the electricity component of annual cost.

Some results of the sensitivity analysis for electricity at the base price of 5 cents/kWh, along with lower (2.5 cents/kWh) and higher (10 cents/kWh) prices, are shown in Figures 3-5. Figure 3 shows the results for bulk storage systems sized for 8-hr discharge per day. Figure 4 shows results for DG systems operating 4 hours per day. Figure 5 presents results for 1-second PQ systems.

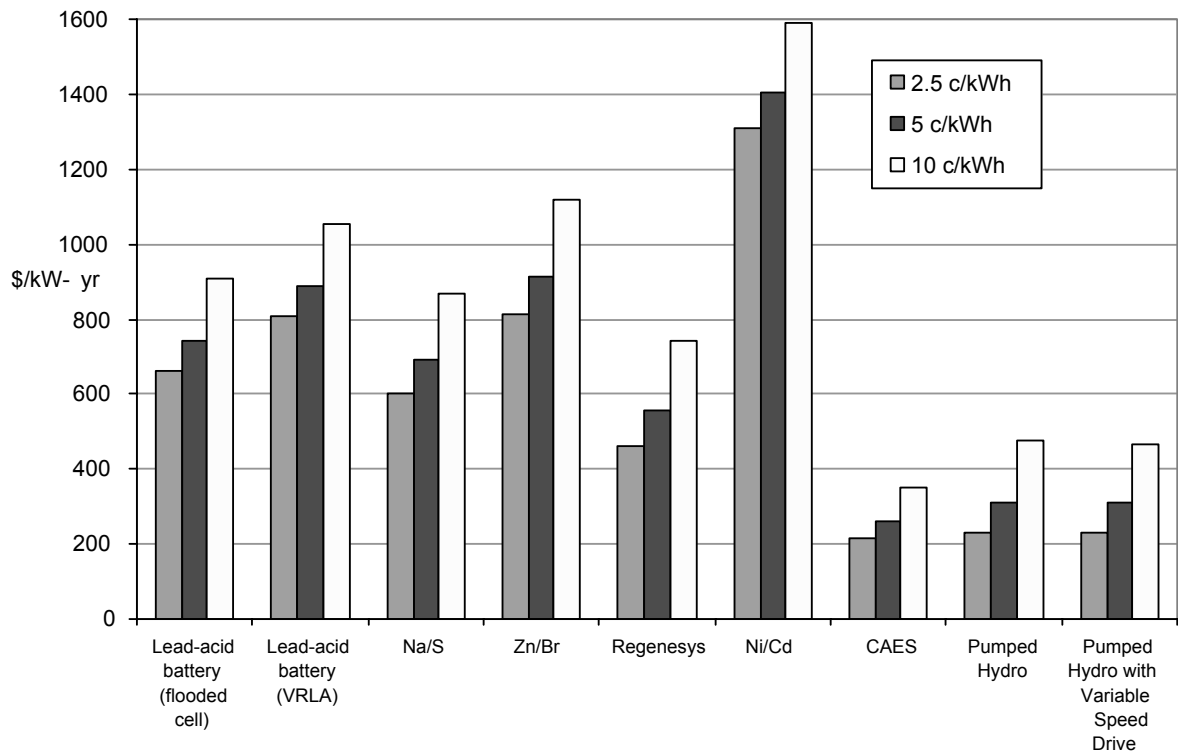


Figure 3. Sensitivity of Total Annual Cost to Electricity Price for 8-hr Bulk Energy Storage Systems

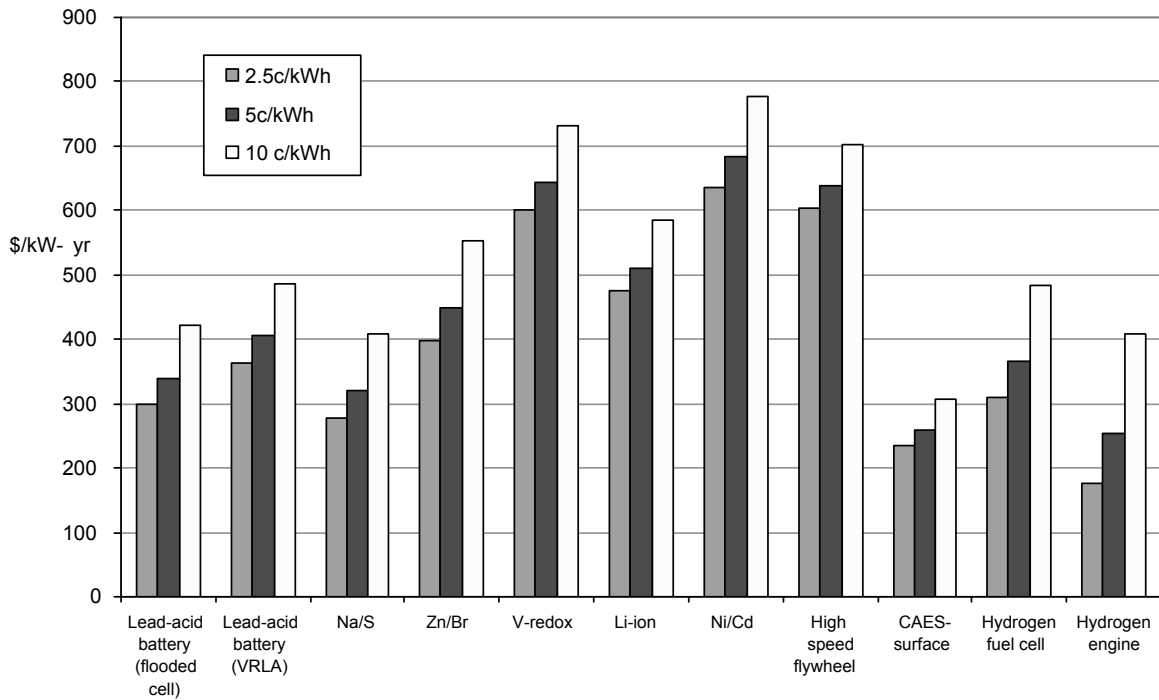


Figure 4. Sensitivity of Total Annual Cost to Electricity Price for 4-hr Distributed Generation Systems

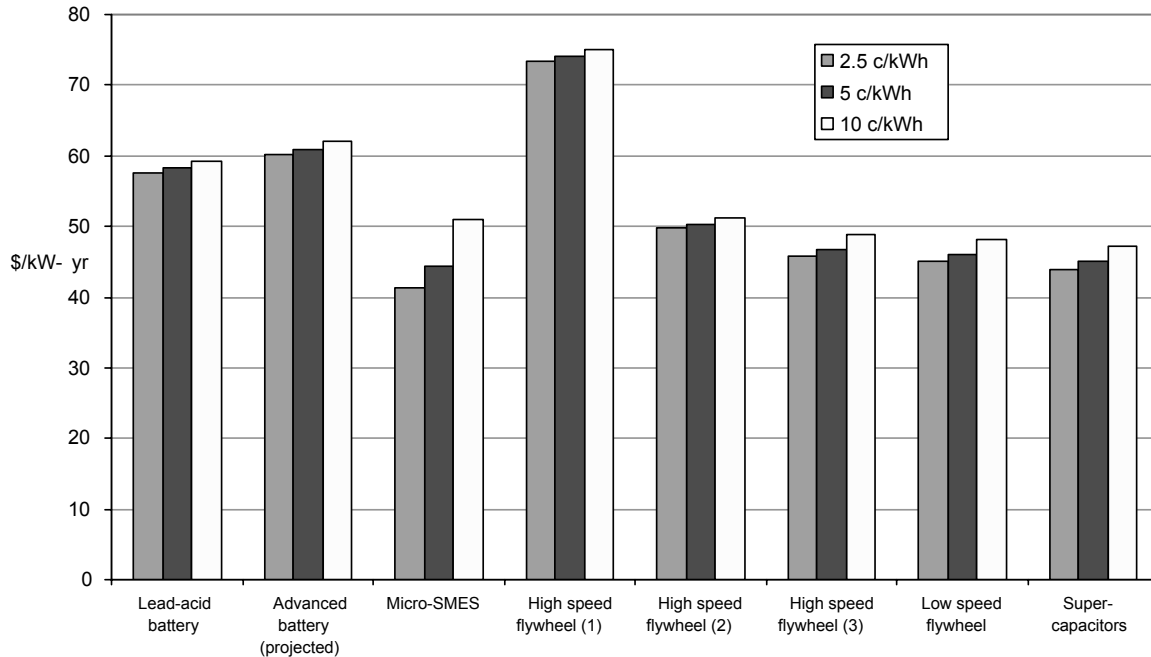


Figure 5. Sensitivity of Total Annual Cost to Electricity Price for 1-sec Power Quality Systems

For most of the bulk storage and DG technologies, the overall impact on annual cost of varying the electricity by a factor of four from lowest price to highest price is less than 30%, with a minimum impact of 11%. However, several systems are more significantly impacted. These are the hydrogen-based systems, which are relatively inefficient and operate an electrolyzer most hours of the day. In this case, doubling the cost of electricity increases the annual cost by as much as 60%. In contrast, most PQ systems are fairly insensitive to electricity price. Varying the price by a factor of four causes less than a 5% variation in annual cost for most systems. Only micro-SMES systems show greater sensitivity due to the refrigeration electric load.

System Life Sensitivity - Results

Another important factor in energy system cost is the system life. Early technology development was focused on bulk storage for applications such as load-leveling. These units were envisioned as part of a central power system and expected to meet life-time specifications similar to other generation equipment. Historically, a typical value for economic calculations has been 20 years. This value was used in the previous studies. For modern distributed and end-use systems installing advanced technologies, 20 years is considered likely to be too long. Therefore, in the current study, sensitivity to system life expectations has been investigated. This assumption affects not only the economic calculations of present value, but more importantly, the replacement costs for components with limited life. As discussed in the precursor study, many of the energy storage technologies under consideration (especially batteries) require partial or major replacements within ten years.

As indicated previously in Table 1, sensitivity analysis was carried out for DG and PQ systems with shorter than 20-year life. Specifically, analysis was performed for systems having 10-year life. This impacts replacement costs, i.e., reduces or eliminates them. At the same time, the carrying charge rate is increased (from 12% to 15%), thus increasing the capital component. Results are shown in Figures 6 and 7 for 4-hr DG systems and 1-sec PQ systems, respectively. In most DG battery cases, the increase in the capital carrying charge was more than offset by the reduced replacement cost. For those DG technologies where a longer system life with little or no replacement is expected, the shorter repayment period results in higher annual costs. For all PQ cases, the shorter repayment period results in higher annual costs because capital carrying charges dominate the system costs.

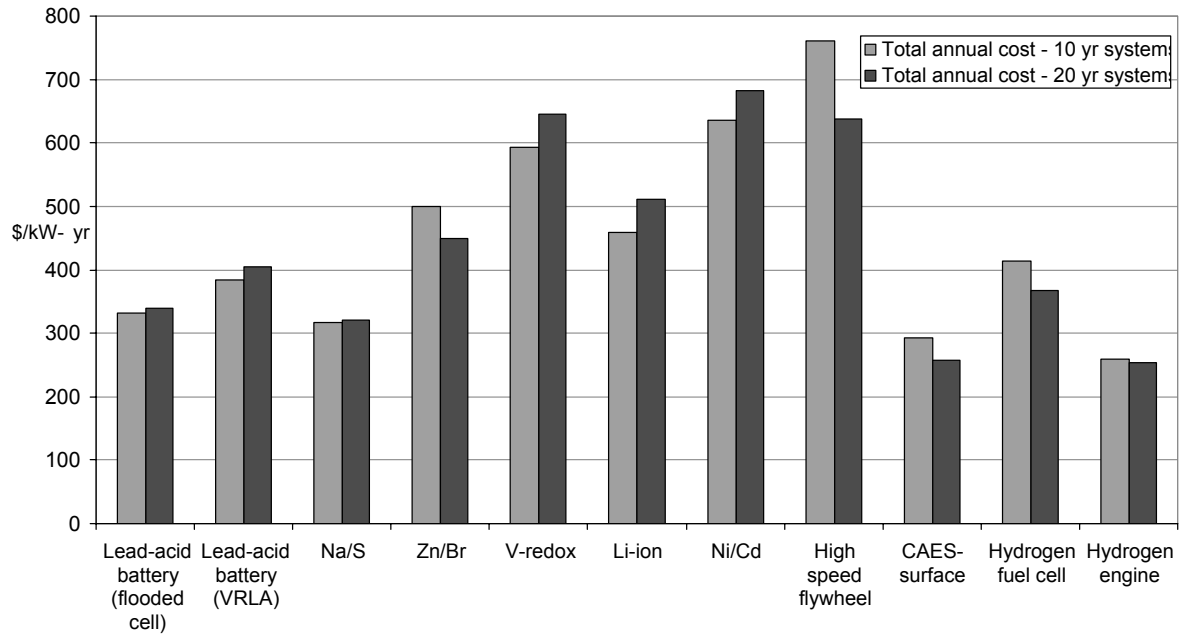


Figure 6. Sensitivity of Total Annual Cost to System Life Assumption for 4-hr DG Systems

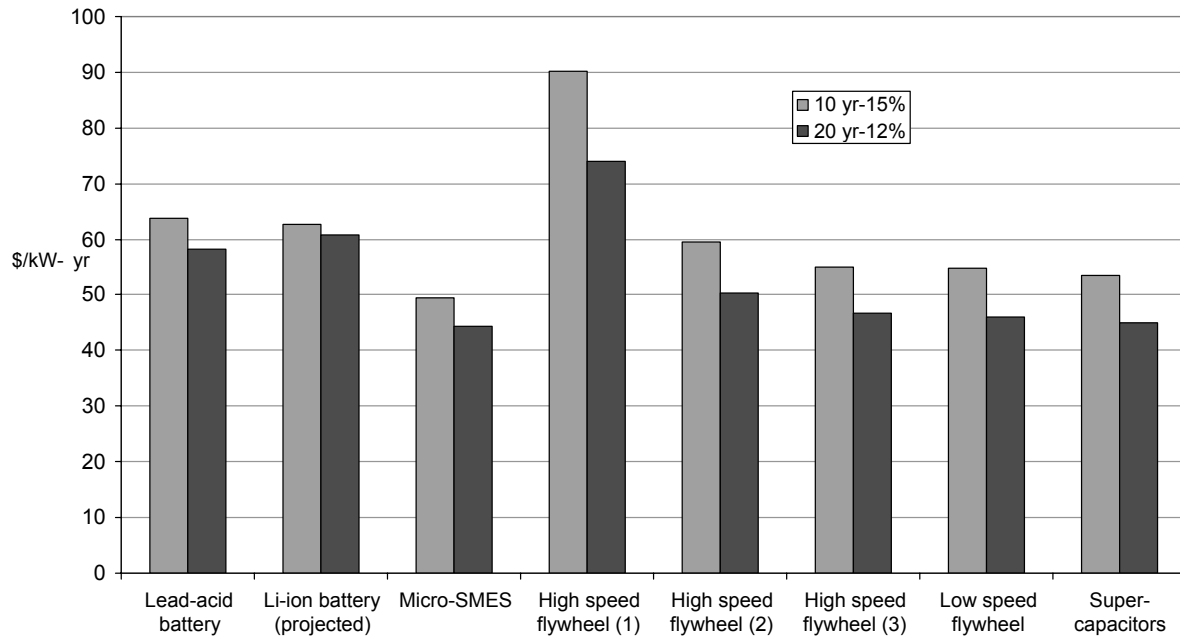


Figure 7. Sensitivity of Total Annual Cost to System Life Assumption for 1-sec PQ Systems

Preliminary Conclusions and Plans

Some preliminary conclusions from the current study include:

- Life-cycle analysis provides more information than capital cost alone, especially for bulk energy storage and DG systems.
- Life-cycle costs of all systems show some sensitivity to electricity prices, but the comparison between technologies is most affected for hydrogen-based systems that include an electrolyzer.

- As structured in this study, natural gas prices affect only CAES systems, but could also be reflected in electricity prices.
- A shorter system life assumption is most beneficial for battery systems operating in DG mode because the reduced replacement requirement more than offsets the higher capital carrying charge. For DG systems designed with a higher life expectation, and for all PQ systems, the shorter repayment period results in higher annual costs.

Ongoing work is being performed to include additional sensitivity analysis, to add a UPS application and several technologies and cost components, to consider siting issues and costs, and to match the cost analysis with benefits assessments being performed separately.

References

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3. Susan M. Schoenung and William V. Hassenzahl, *Long- vs. Short-Term Energy Storage Technologies Analysis: A Life-Cycle Cost Study*, Sandia Report SAND2003-2783, August 2003.