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## **Benefit/Cost Framework for Evaluating Modular Energy Storage**

**A Study for the DOE Energy Storage Systems Program**

Susan M. Schoenung and Jim Eyer

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## **A Study for the DOE Energy Storage Systems Program**

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### **Abstract**

The work documented in this report represents another step in the ongoing investigation of innovative and potentially attractive value propositions for electricity storage by the United States Department of Energy (DOE) and Sandia National Laboratories (SNL) Energy Storage Systems (ESS) Program. This study uses updated cost and performance information for modular energy storage (MES) developed for this study to evaluate four prospective value propositions for MES. The four potentially attractive value propositions are defined by a combination of well-known benefits that are associated with electricity generation, delivery, and use. The value propositions evaluated are: 1) transportable MES for electric utility transmission and distribution (T&D) equipment upgrade deferral and for improving local power quality, each in alternating years, 2) improving local power quality only, in all years, 3) electric utility T&D deferral in year 1, followed by electricity price arbitrage in following years; plus a generation capacity credit in all years, and 4) electric utility end-user cost management during times when peak and critical peak pricing prevail.

## **Acknowledgments**

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## Acronyms and Abbreviations

CAES	compressed air energy storage
CPP	critical peak pricing
DER	distributed energy resource
DG	distributed generation
DOE	Department of Energy
DUA	Distributed Utility Associates
ESS	energy storage system
$I^2R$	resistive losses (current squared * resistance)
kV	kiloVolt
kVA	kiloVolt-Amps
kW	kiloWatt
kWh <sub>out</sub>	kiloWatt-hours output
Li-ion	lithium-ion
MES	modular energy storage
MW	megawatts
Na/S	sodium/sulfur
Ni/Cd	nickel/cadmium
O&M	operation and maintenance
PCS	power conversion system
PG&E	Pacific Gas and Electric Company
PW	present worth
PQ	power quality
SNL	Sandia National Laboratories
T&D	transmission and distribution
UPS	uninterruptible power supply
VAR	volt-amp reactive
V-redox	vanadium-redox
VRLA	valve-regulated lead-acid
Zn/Br	zinc/bromine

## Conventions Used in this Report

For simplicity, units of power, or load carrying capacity, will be expressed in units of kilowatts (kW), although in some cases units of kiloVolt-Amps (kVA) may be more appropriate. For example, utility equipment is rated in units of kVA rather than kilowatts. For the purposes of this study, the distinction is not important.

The term transmission and distribution (T&D) is used throughout this document. It is important to note that the focus of this study is on distribution and subtransmission systems, rather than the higher voltage, higher capacity, “bulk” transmission systems. Two key reasons for this are: a) criteria used to decide whether to add transmission capacity are somewhat different than those used to justify a subtransmission or distribution upgrade, and b) the roles for distributed energy resources (DERs) that serve the transmission system directly (e.g., to stabilize voltage or frequency) may be different than the roles served by DER used for subtransmission and distribution capacity (i.e., used in lieu of actually *transmitting* energy). So, in this report, the term T&D refers to *subtransmission* and distribution.



# Executive Summary

## ***Purpose***

The work documented in this report was undertaken for three key purposes:

1. Often, benefits and costs developed in previous energy storage studies were computed using different financial bases. This work reconciles those financial bases so that costs and benefits are expressed using consistent bases and assumptions.
2. The Energy Storage Systems (ESS) Program management at Sandia wanted to update their storage technology cost and performance information to reflect state-of-the-art.
3. Results in this report reflect another next step in the ongoing investigation of innovative and potentially attractive value propositions for electricity storage by the Department of Energy (DOE) and Sandia National Laboratories (SNL) ESS Program.

## ***Scope***

The scope of this report covers:

1. Characterization of a basic framework for evaluating the benefits and costs for modular energy storage (MES) that is used for various applications. The framework includes common financial bases and consistent assumptions for both cost and benefit calculations.
2. Up-to-date MES system cost and performance data for ten leading electricity storage technologies.
3. Estimates of MES costs and benefits for four, possibly attractive electric utility-related value propositions.

## ***Intended Audience***

The intended audience for this report includes utilities and electricity providers (planners, engineering, and management), electricity storage vendors, technology developers, system integrators and advocates, and energy policymakers and researchers.

## ***Key Results and Conclusions***

Of the ten technologies considered, lead-acid batteries appear to have the greatest potential for attractive benefit / cost ratios in the combined T&D deferral / power quality value proposition. In general, to improve the benefit / cost ratio for all cases, costs for energy storage systems must be reduced. Opportunities for combining benefit values have the greatest potential to result in attractive benefit/cost ratios for all technologies.



# 1. Introduction

This work combines results from previously separate research sponsored by the U.S. Department of Energy (DOE) Energy Storage Systems (ESS) Program at Sandia National Labs (SNL). A primary objective is to establish a framework for expressing electricity storage benefits and costs using consistent assumptions and bases. The framework is exercised using up-to-date cost and performance projections for leading modular energy storage (MES) technologies.

The evaluation compares costs and benefits for four, potentially attractive uses of MES (value propositions). They involve use of MES for:

Value Proposition 1: transportable MES for electric utility transmission and distribution (T&D) equipment upgrade deferral in even numbered years and for improving local power quality in odd numbered years, at different locations.

Value Proposition 2: transportable MES for improving local power quality in all years, at different locations.

Value Proposition 3: electric utility T&D deferral in year 1, followed by electricity price arbitrage in following years; plus a generation capacity credit in all years.

Value Proposition 4: electric utility end-user cost management during times when peak and critical peak pricing prevail.

The value propositions evaluated include financial benefits identified in previous work by Distributed Utility Associates (DUA) sponsored by the DOE ESS Program [1] and the California Energy Commission [2], and using costs based on previous work by Longitude 122 West and Advanced Energy Analysis for the DOE ESS Program that were updated for this study [3, 4]. This work is a follow-on to related analyses performed previously for the ESS Program [5, 6].



## 2. Methodology Description

### **Financial Assumptions**

One objective of this study was to establish generic criteria for calculating energy storage benefits and costs, using consistent bases and assumptions. This section describes the approach and assumptions used for financial analysis.

Readers should note that two key assumptions – storage system service life and the discount rate used to calculate present worth over the service life – are intended to represent a *generic* circumstance. For any *specific* circumstance, other more situation-specific assumptions may be appropriate. A general indication of the effect that service life and discount rate have on lifecycle financials is provided later.

Benefits and costs associated with storage system use are calculated using common financial bases, shown in Table 1. Most notable, in order of significance, are: a) ten year storage system service life, b) 10% discount rate, and c) 2.5% annual price escalation (inflation) rate.

**Table 1. Assumptions for Life Cycle Benefit and Cost Analysis**

Parameter	Value
Service life	10 years
Discount rate	10%
General inflation rate	2.5%
Utility Fixed Charge Rate	11%
Fuel cost, natural gas (for surface CAES only)	5 \$/MBTU
Electricity cost, charging	5 ¢/kWh

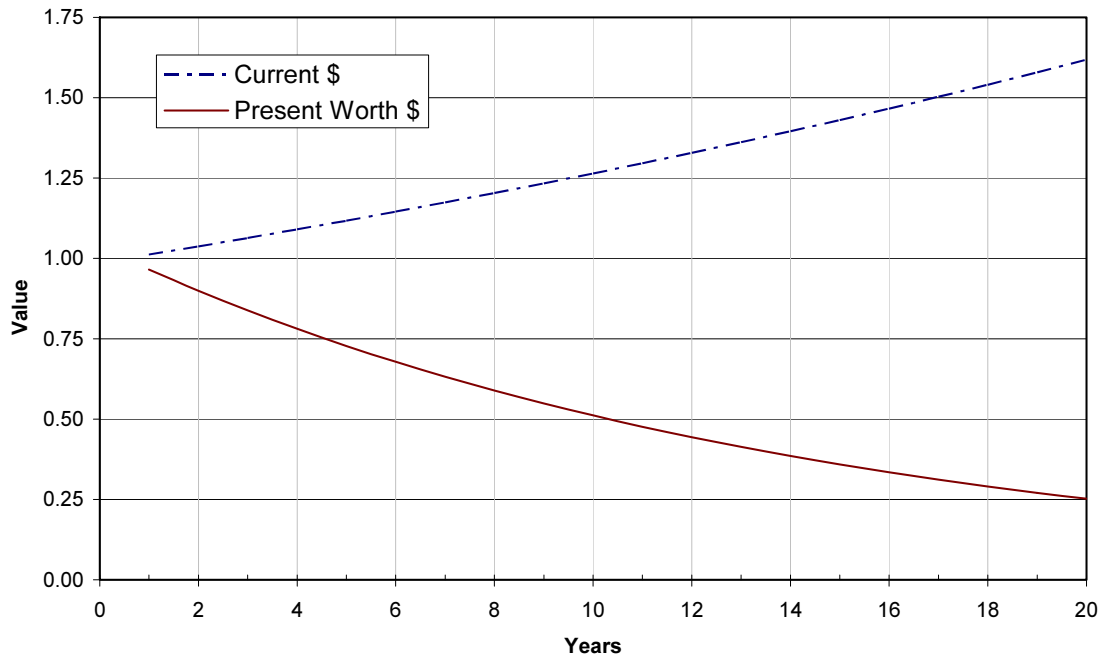
Those three criteria – service life, discount rate, and inflation – are used to calculate the Present Worth (PW) Factor. The PW Factor provides a simplified way to represent a discounted present worth of a stream of regular revenues or payments, for a given number of years.

### **Present Worth Factor**

Consider a simple example as an illustration of how the PW factor is used. In year 1 of a project, the total cost is \$1.00. In subsequent years, that annually recurring cost is assumed to escalate at 2.5% per year, due to inflation. The upper plot in Figure 1 indicates annual cost as it escalates from year to year. The values plotted are referred to as “current dollar” values.

The lower plot in Figure 1 indicates the present worth of the current dollar values (shown in the upper plot), after applying the discount rate for the respective number of years. Those “discounted” values are summed over all years of the project to calculate the present worth for all years. Note the dramatic impact that discounting at 10% per year has on the final value.

The curves in Figure 1 show that, for a cost of \$1 in the first year, after ten years of inflation at 2.5%/year, the cost in year ten would be about \$1.28 (current dollar value). Discounting that same \$1 (in year ten) at 10%/year results in a present worth or discounted value of about 50 cents (for year ten).

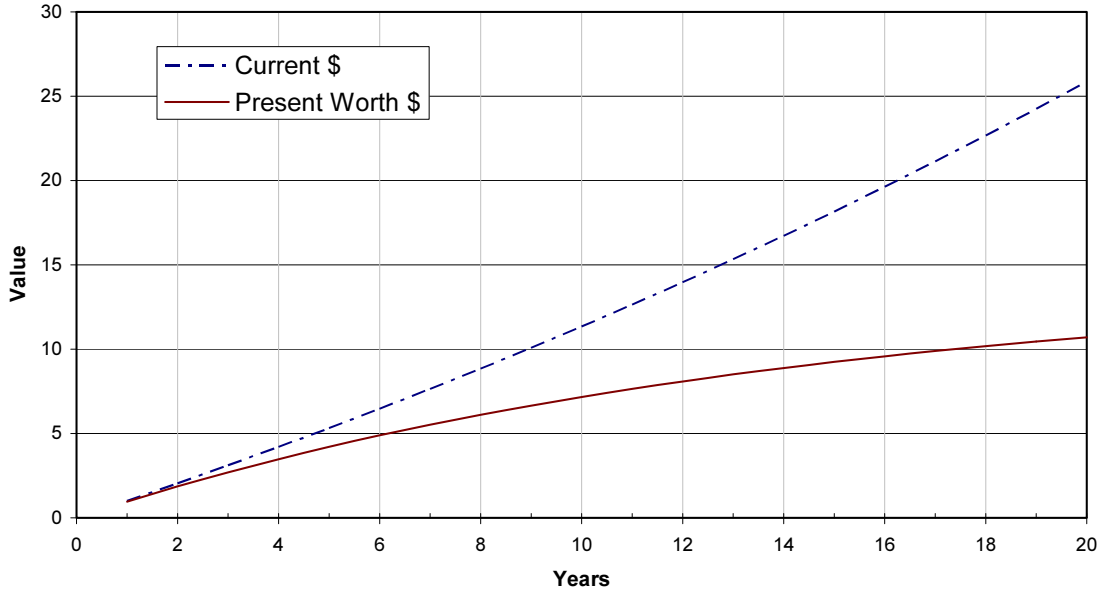


Escalation Rate: 2.5%/yr., Discount Rate: 10.0%/yr.

**Figure 1. Annual Current and Present Worth Values for \$1 in Year 1.**

Figure 2 shows *cumulative* values for the same two series shown in Figure 1. That is, they are the cumulative values for escalated cost and for discounted annual values. For a given year, the value of the upper plot represents the cumulative amount reflecting a cost of \$1 in year 1, escalating at 2.5%/year (current dollar value). The lower plot represents the cumulative amount when summing annual present worth (discounted) values reflecting a 10% discount rate.

Figure 2 indicates that, after ten years, the cumulative value of costs incurred annually – beginning with \$1 in year 1 and escalating at 2.5% each year – is about \$12.00. When discounting that amount for ten years, the resulting present worth is about \$7.17. That reflects a Present Worth Factor (PW factor) of 7.17 for a project lasting ten years if inflation is 2.5%/year and the discount rate is 10%/year.



Escalation Rate: 2.5%/yr., Discount Rate: 10.0%/yr.

**Figure 2. Cumulative Current and Present Worth Values for \$1 in Year 1.**

The equation for the PW factor for a ten-year service life is as follows:

PW factor =

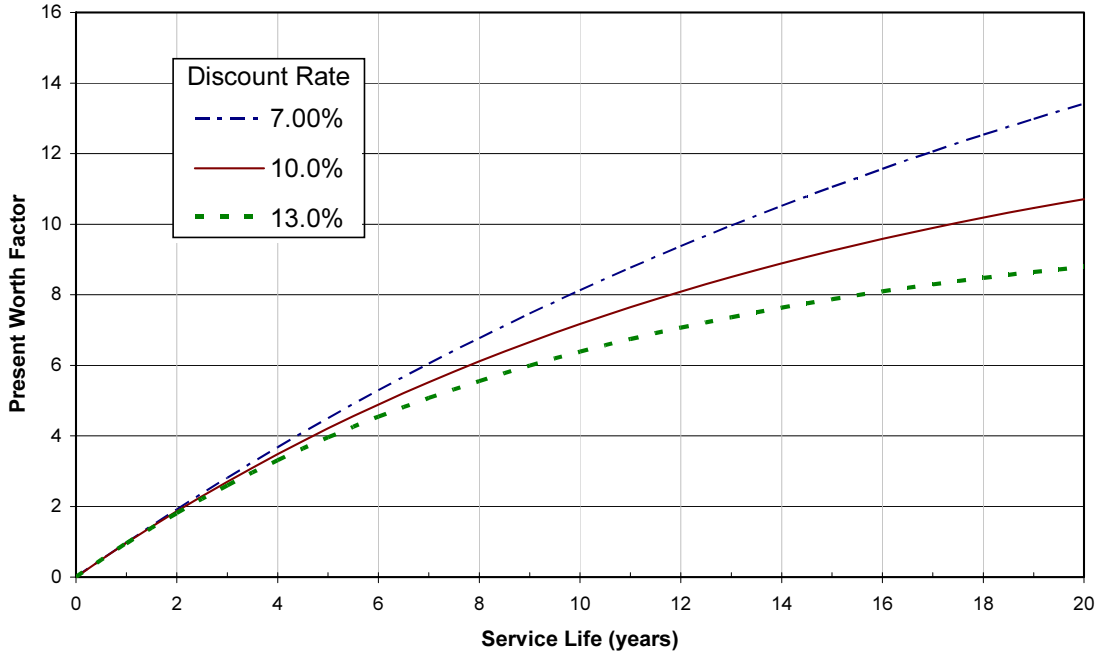
$$\sum_{i=1}^{10} \frac{(1+e)^{i-.5}}{(1+d)^{i-.5}}$$

e = annual price escalation rate (%/year)

d = discount rate (%/year)

i = year

Figure 3 shows PW factors for three discount rates, assuming a cost escalation of 2.5%/year. (The value of “i” is calculated at mid-year.) For a given life/discount rate combination, the PW factor represents the present worth for a stream of values like that described in Figure 2. Note that the plot for the 10% discount rate in Figure 3 represents the same values as the lower plot in Figure 2.



Escalation Rate: 2.5%/yr. Mid Year Convention.

**Figure 3. Present Worth Factors for various Service Lives and Discount Rates.**

Figure 3 allows for quick comparisons of annually recurring costs and benefits for various project service lives and discount rates.

Consider another example. Assume that a storage plant will cost \$100,000 in the first year of operation. That annual cost is expected to escalate at 2.5% per year over the ten year service life. The owner uses a 10% discount rate. The present worth of all costs (before tax) is about \$717,000 (7.17 PW factor \* \$100,000 in year 1). For comparison, look at the outcomes for the other discount rates in Figure 3. For a first year cost of \$100,000, the present worth (over ten years) is about \$813,000 if the discount rate is 7%/year and the ten year present worth is about \$630,000 if the discount rate is 13%/year.



### 3. Value Propositions

A value proposition is comprised of all benefits and all costs, including risk, that are associated with an investment or purchase. Four value propositions are used to illustrate the benefit/cost evaluation framework described in this report. Those value propositions were selected because they involve opportunities for which MES is technically viable and could yield high benefits. Many other value propositions are possible and may show advantages for storage technologies.

Value Proposition 1: transportable MES for electric utility transmission and distribution (T&D) equipment upgrade deferral in even numbered years and for improving local power quality in odd numbered years, at different locations.

Value Proposition 2: transportable MES for improving local power quality in all years, at different locations.

Value Proposition 3: electric utility T&D deferral in year 1, followed by electricity price arbitrage in following years; plus a generation capacity credit in all years.

Value Proposition 4: electric utility end-user cost management during times when peak and critical peak pricing prevail

The assumed operating and design parameters for the four value propositions are listed in Table 2.

**Table 2. Parameters of Value Propositions for Energy Storage Benefit / Cost Analysis**

	Value Proposition 1: Transportable MES for T&D Deferral and PQ	Value Proposition 2: Transportable MES for improving PQ	Value Proposition 3: T&D Deferral Plus Energy Price Arbitrage	Value Proposition 4: Peak Plus Critical Peak Electricity Pricing
Description	1 <sup>st</sup> year deferral, 2 <sup>nd</sup> yr PQ/reliability; move to new location; 3 <sup>rd</sup> year deferral, 4 <sup>th</sup> year PQ, etc.	10 years all power quality	1 year deferral, subsequent years arbitrage	Operate during peak and critical peak hours to avoid time- of-day charges and earn discount
Power range	300 kW – 1 MW	300 kW – 1 MW	500 kW – 2 MW	20 kW – 1 MW
Hours of dispatchable storage	4 - 5 hrs	0.25 – 1 hr	4 – 5 hrs	5 hrs
Hours of operation per year	T&D: 200 hrs/yr PQ: 20 hrs/yr	PQ: 20 hrs/yr	T&D: 200 hrs/yr Arbitrage: 1000 hrs/yr	Critical peak: 60 hrs/yr Total peak: 1600 hrs/yr
Technology issues	Must be moveable, suitable for infrequent use, rapid availability		Routine use, high duty cycle	Routine use, high duty cycle



## 4. Storage Technology

### ***Storage Options Evaluated***

The energy storage technologies evaluated for each value proposition are listed in Table 3. The characteristics of these technologies are derived from previous work found in References 3, 4, and 7.

For value proposition 1, the storage technologies evaluated are those which are movable and which can provide storage for five hours of discharge. Though flywheels are probably not suitable for applications requiring hours of storage, they are suitable for power quality/reliability applications, and are therefore included in the value proposition 1 analysis. Surface Compressed Air Energy Storage (CAES) is evaluated only for value proposition 3, where a moveable resource is not required.

**Table 3. Storage Technologies Evaluated**

<b>Value Proposition 1: Transportable MES for T&amp;D Deferral and PQ</b>	<b>Value Proposition 2: Transportable MES for improving PQ</b>	<b>Value Proposition 3: T&amp;D Deferral Plus Arbitrage</b>	<b>Value Proposition 4: Peak Plus Critical Peak Electricity Pricing</b>
<ul style="list-style-type: none"> <li>• Lead-acid batteries (flooded and VRLA)</li> <li>• Ni/Cd</li> <li>• Na/S batteries</li> <li>• Li-ion batteries</li> <li>• Zn/Br batteries</li> <li>• V-redox batteries</li> <li>• High-speed and low-speed flywheels</li> <li>• Lead-carbon asymmetric caps</li> <li>• Hydrogen fuel cell</li> </ul>	<ul style="list-style-type: none"> <li>• Lead-acid batteries (flooded and VRLA)</li> <li>• Ni/Cd</li> <li>• Li-ion batteries</li> <li>• Zn/Br batteries</li> <li>• High-speed and low-speed flywheels</li> <li>• Lead-carbon asymmetric caps</li> </ul>	<ul style="list-style-type: none"> <li>• Lead-acid batteries (flooded and VRLA)</li> <li>• Na/S batteries</li> <li>• Ni/Cd</li> <li>• Li-ion batteries</li> <li>• Zn/Br batteries</li> <li>• V-redox batteries</li> <li>• Surface CAES</li> <li>• Lead-carbon asymmetric caps</li> <li>• Hydrogen fuel cell</li> </ul>	<ul style="list-style-type: none"> <li>• Lead-acid batteries (flooded and VRLA)</li> <li>• Ni/Cd</li> <li>• Na/S batteries</li> <li>• Li-ion batteries</li> <li>• Zn/Br batteries</li> <li>• V-redox batteries</li> <li>• Lead-carbon asymmetric caps</li> <li>• Hydrogen fuel cell</li> </ul>

### ***Storage Cost and Performance***

The cost approach is the same as that in Reference 3. The cost and performance data for the various storage technologies were derived based primarily on Reference 3, although more up-to-date information was also used. Notably, the authors found limited changes during the years 2005 and 2006, especially with regard to equipment (system) installed cost.

Specific exceptions to Reference 3 include:

- Replacement costs were reduced for storage components used for value proposition 1 in this study because the number of operating cycles is far less than the five full discharge / recharge cycles per week that were assumed in the previous work.
- Vanadium-redox battery costs have dropped: for this study, energy-related equipment cost is \$350/kWh, compared with \$600/kWh in Ref. 3. [8]
- Lead-carbon asymmetric capacitors were not included in Ref. 3, but have been added based on Ref. 9 and 10. The assumed costs are \$500/kWh for the energy-related equipment component and \$350/kW for the power-related equipment.

Thus, the capital cost assumptions for storage technologies considered in this study are shown in Table 4. Balance of Plant includes the auxiliary components outside of the storage subsystem or power converters. For some technologies, these costs are integral to the power system.

**Table 4. Storage Technologies Evaluated and Costs**

<b>Technology</b>	<b>Energy- Related Cost (\$/kWh)</b>	<b>Power-Related Cost (\$/kW)</b>	<b>Balance of Plant (\$/kW)</b>
Lead-acid Batteries (Flooded Cell)	150	175	50
Lead-acid Batteries (VRLA)	200	175	50
Ni/Cd	600	175	50
Zn/Br	400	175	0
Na/S	250	150	0
Li-Ion	500	175	0
V-redox	350	175	30
Lead-carbon asymmetric caps	500	350	50
CAES-surface	120	550	50
High-speed flywheel	1,000	300	0
Low-speed flywheel	380	280	0
Hydrogen fuel cell	15	1500	0
Electrolyzer (to accompany fuel cell)	None	300	None

As a possibly helpful comparison, consider the costs for state-of-the-art small uninterruptible power supplies (UPSs) with ratings ranging from 700 VA to 30 kVA shown in Table 5, below.

**Table 5. State-of-the-art UPS Ratings and Prices**

Device	VA	Minutes	Price (\$)	\$/kVA	\$/kVA-hour
LIEBERT - UPSTATION GXT2 700VA UPS- RM 2U 17MIN 4RCPTL	700	17	601	858	3,028
TRIPP LITE - SMART OL 1000VA RM TWR 2U-UPS 6RCPTL USB SER SLOT	1,000	6	443	443	4,430
MGE UPS SYSTEMS INC - PULSAR EX RT 3200VA RM-OL RACK/TWR UPS	3,200	6	1,130	353	3,530
Tripp Lite SmartOnLine SU7500RT3U - UPS - 6 kW - 7500 VA	7,500	9	3,017	402	2,682
APC - SMARTUPS VT OL 30KVA RM 3-PH 208V 5 BATT PDU STRTU	30,000	13.7	27,000	900	3,942

Notes:

- This table does not constitute an endorsement or recommendation of the listed products or suppliers.
  - Power rating in units of Volt-Amps.
  - Typically 1.2 to 1.3 Volt-Amps are required for each Watt of load.
- (source: [www.techonweb.com](http://www.techonweb.com))



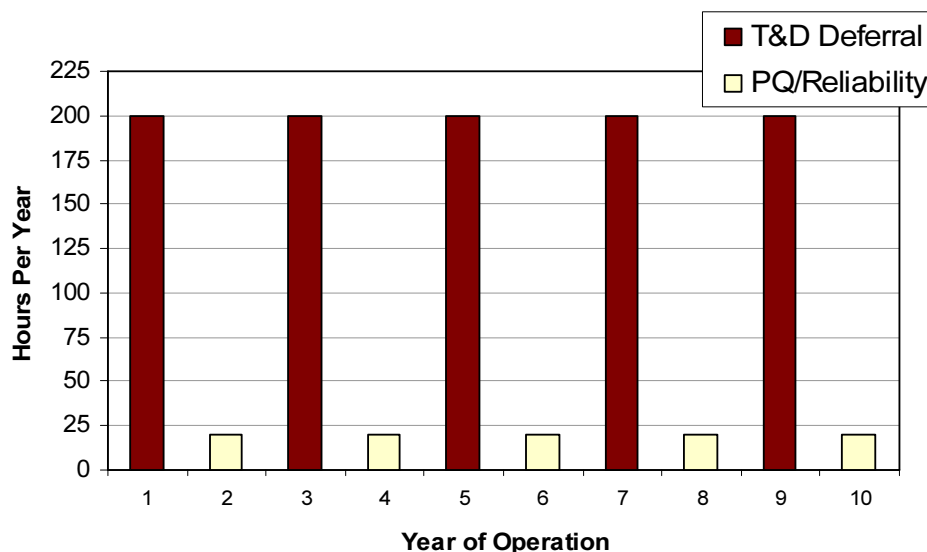
## 5. Results: Benefit – Cost Comparisons

What follows is a summary of results and key assumptions. The results are benefit/cost values for the various MES options that were evaluated for the respective value propositions. Additional details are provided for value proposition 1, to illustrate the framework used to derive the results.

### ***Value Proposition 1: Transportable MES for T&D Deferral and Power Quality***

This value proposition involves transportable MES that is used in odd numbered years for high or relatively high value utility T&D upgrade deferral, and then moved for use in even years to improve localized power quality or reliability, over its ten year life.

A 5-hr energy storage system is assumed. Figure 4 indicates the operation hours assumed for each of the ten years of operation.



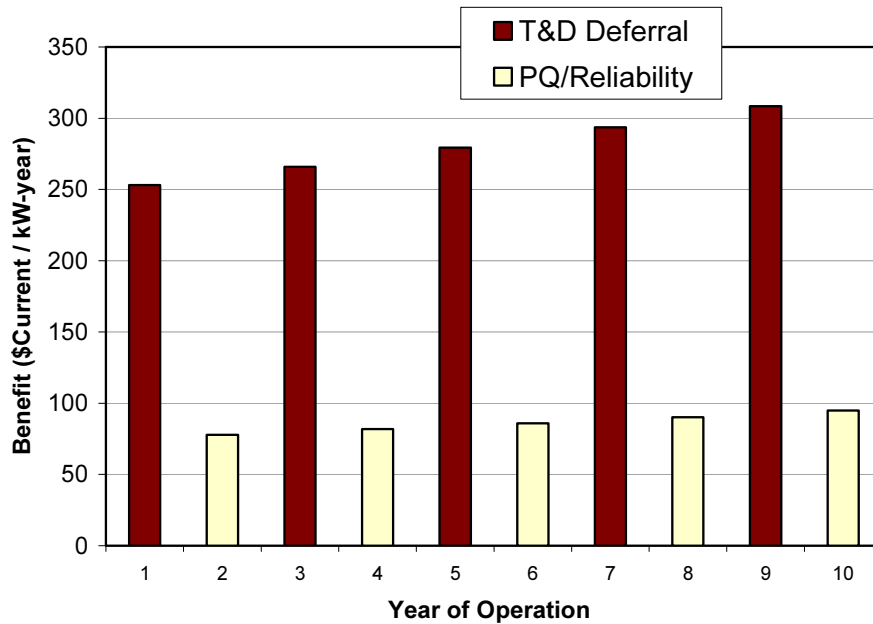
**Figure 4. T&D Deferral and Power Quality: Hours of Operation per Year.**

### **Benefit**

The financial benefit for T&D upgrade deferral is assumed to last for one year at a given location, after which it becomes cost-effective to proceed with the T&D upgrade. That is a conservative assumption because MES may allow for multi-year deferrals.

The financial benefit for improving power quality and reliability arises when the MES is used to a) shield loads from electrical effects caused by short duration power quality events, and b) pick up load during long duration power outages, to ride through the outage or to allow for an orderly shut-down.

The annual benefit ( $\$Current$ ) for each of ten years is shown in Figure 5. Those values are estimated by assuming a benefit of  $\$250/kW$  T&D deferral ( $\$Constant$ ) and a power quality benefit of  $\$75/kW$  ( $\$Constant$ ). [10]



**Figure 5. T&D Deferral and Power Quality: Benefits ( $\$Current/kW$ ).**

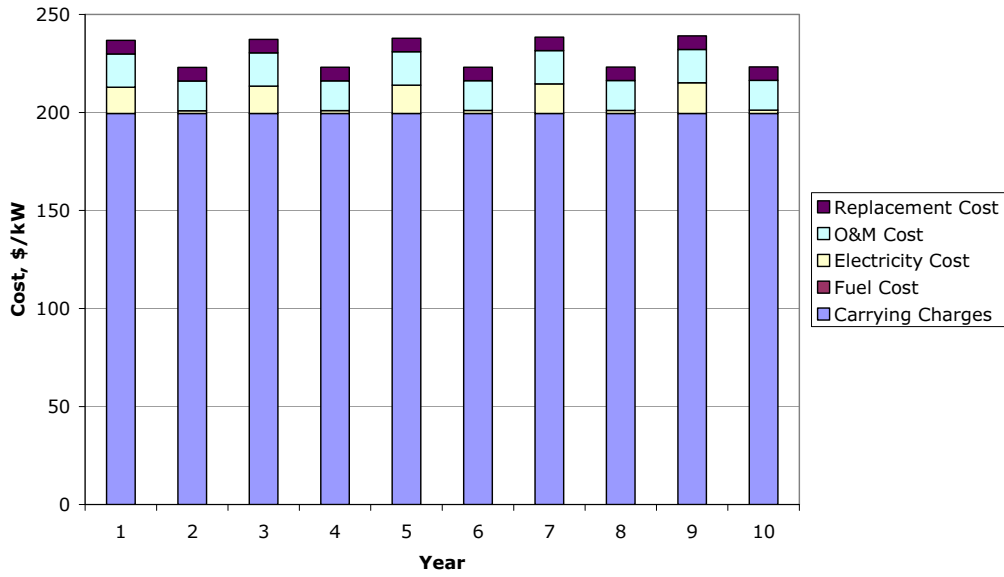
### Cost

As an example, a representative MES system is used to illustrate the cost breakdown. The representative MES is a state-of-the-art flooded lead-acid battery whose roundtrip efficiency is 75%. The costs to own and operate that system are shown in Figure 6.

Cost elements include installed capital equipment, maintenance, battery replacement, and the cost for charging energy. The replacement cost is significantly reduced from the previous study because the system is cycled much less frequently.

As noted in Section 4, MES used for T&D deferral and PQ is cycled much less frequently than was assumed in the original study, resulting in a proportional reduction in annual replacement costs. In the original cost study, the replacement period for the energy storage component of the system was assumed to be six years, and a complete cell replacement was assumed. The system was assumed to operate 5 days per week, 50 weeks per year, or a total 1,250 hours per year for a 5-hour system. In this current scenario, however, the system is cycled infrequently.

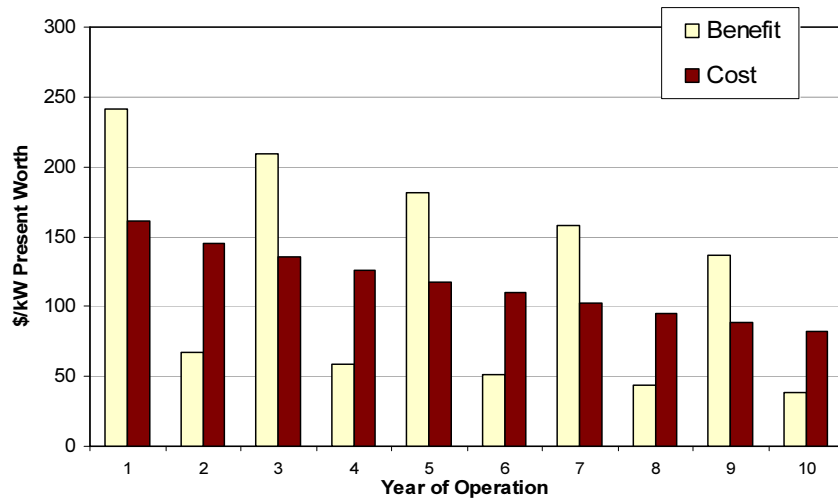




**Figure 6. T&D Deferral and Power Quality: Current-year Cost Components for a flooded Lead-Acid Battery System (\$/kW).**

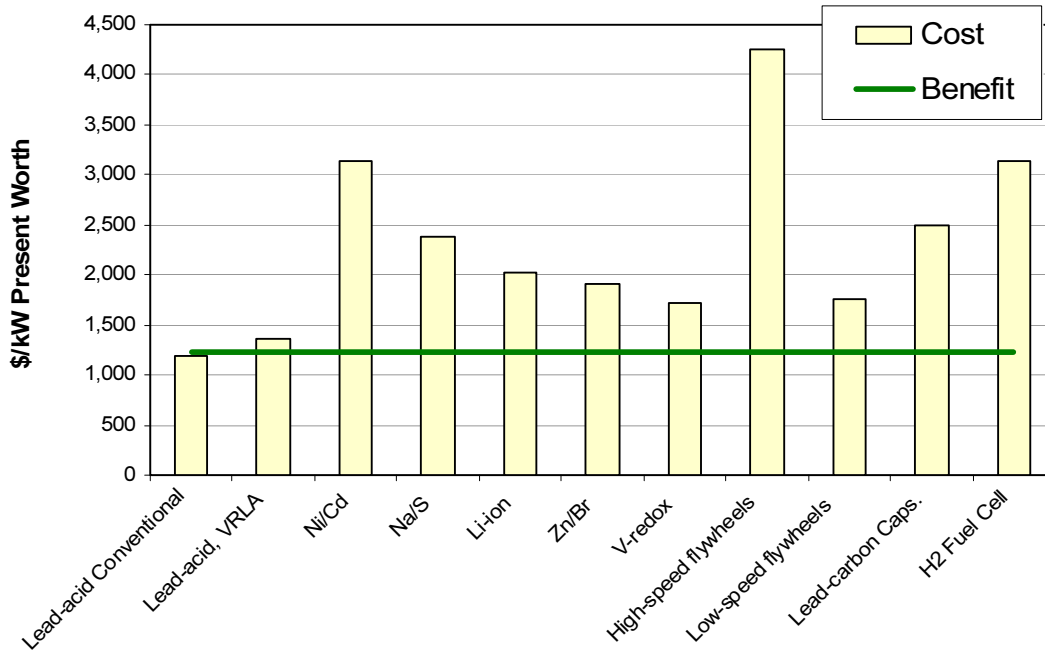
### Benefit/Cost Results

Figure 7 shows the present value of a) benefits, and b) costs for the representative storage type. When applying the generic financial assumptions, present worth of benefits over 10 years is \$1,203/kW. The 10-year present worth of cost, assuming the lower annual replacement cost is \$1,200/kW. Thus, if replacement costs can be reduced as indicated above, it is possible to achieve a benefit / cost ratio slightly greater than one.



**Figure 7. T&D Deferral and Power Quality: Present Worth of Benefits and Costs (\$/kW) for a flooded Lead-Acid Battery System.**

Other technologies are technically viable for value proposition 1. Based on costs from the previous study – with an adjustment of the replacement cost to account for reduced cycling – the present worth of benefits and costs over 10 years are shown in Figure 8 for all storage technologies evaluated. Note that lead-acid batteries have the lowest cost and thus have the highest benefit/cost ratio.



**Figure 8. T&D Deferral and Power Quality: Present Worth of Benefits and Costs over 10 years.**

### ***Value Proposition 2: Improving Power Quality/Reliability***

This value proposition involves use of MES for localized or on-site power quality improvement and/or to improve localized electric service reliability. Improving PQ and reliability is an especially attractive use of MES because: a) the relatively modest amount of storage (discharge duration) required, and b) the small number of lifetime discharges required, especially full discharge. That is especially true for MES technologies that have a high incremental cost for energy storage, i.e., long discharge duration.

In this case, a somewhat conservative discharge duration of 15 minutes was assumed. This is conservative in the sense that in many cases much less energy storage is needed.

#### **Benefit**

The financial benefits for improving power quality and reliability arise when the MES is used to: a) shield loads from electrical effects caused by short duration power quality events, and b) pick up load during long duration power outages, to ride through the outage or to allow for an orderly shut-down.

The annual benefit (\$Current) for power quality for each of ten years is the same as in value proposition 1: \$75/kW (\$Constant).

### Benefit/Cost Results

As shown in Figure 9, most MES types have attractive benefit / cost ratios for PQ/reliability applications.

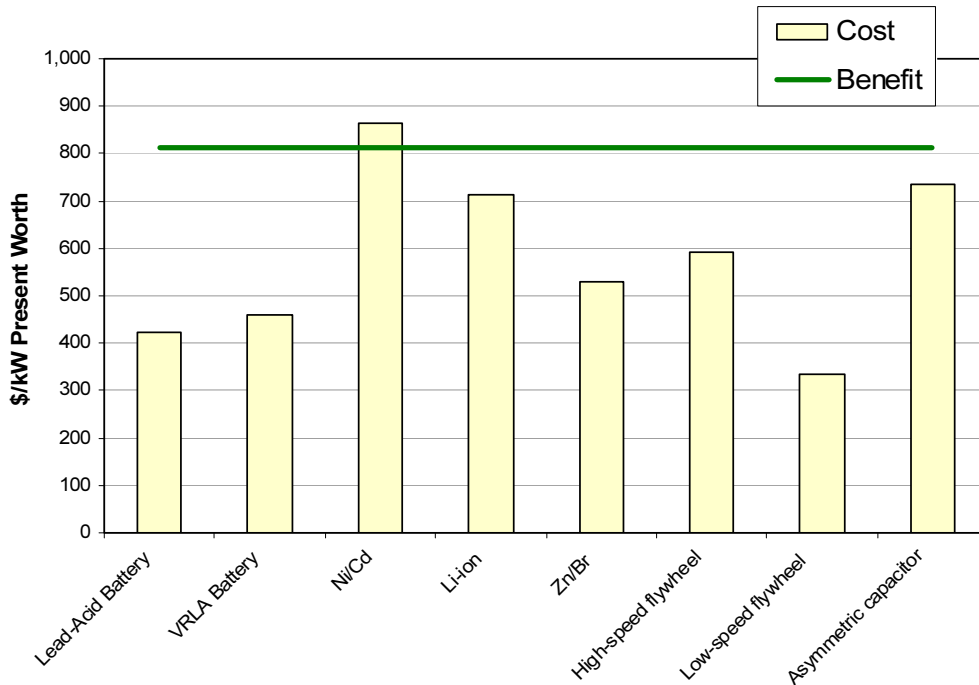


Figure 9. MES Technologies’ Benefits and Costs for Power Quality.

### Value Proposition 3: T&D Deferral Plus Energy Price Arbitrage and Central Generation Capacity Credit

For this value proposition, an energy storage system with five hours of discharge duration is deployed to defer a T&D upgrade for one year. After the first year, the system remains at the original location and is used for energy price arbitrage. It also receives a generation capacity credit equal to the annual cost avoided for additional central generation capacity in each of ten years.

#### T&D Deferral

For this value proposition, a “very high” T&D deferral benefit of \$650/kW (of storage) is assumed for the first year of MES operation, which is the only year for which the T&D deferral benefit accrues. That amount represents the highest 10% (most valuable) opportunity for T&D deferral. [2] Discharge operation for 200 hours per year (at full load equivalent) is assumed for T&D deferral.

## Energy Price Arbitrage

Electric energy price arbitrage exploits wholesale electricity price volatility and diurnal variability. Benefits accrue when storage is charged using low-priced off-peak energy, for sale when energy price is high.

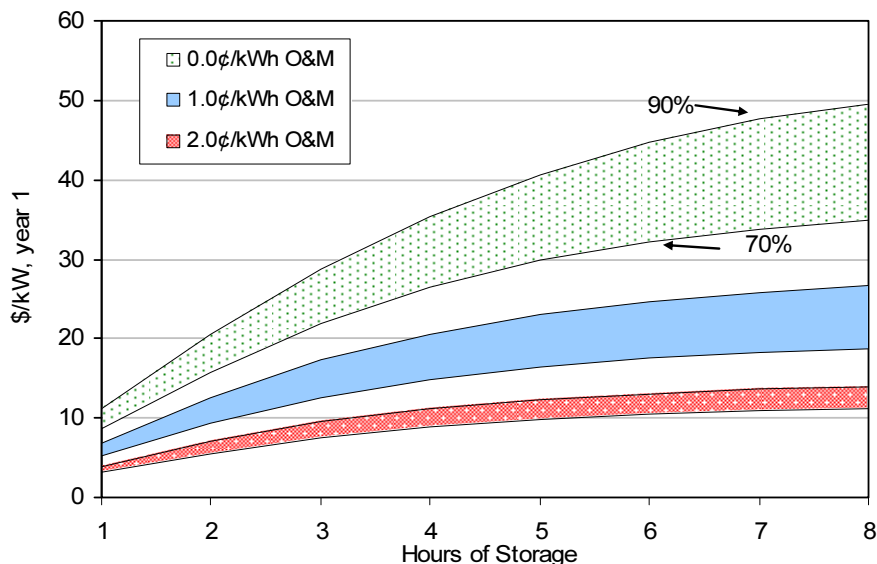
Storage losses or inefficiencies add to the fully burdened discharge cost. Fully burdened incremental discharge cost includes cost for charging energy, energy lost during the charge/discharge cycle, plus variable operating cost. Variable operating cost is comprised of the incremental cost for regular maintenance and the incremental cost for replacement of the storage medium, for each kWh discharged. So, for a given transaction, the *net benefit* (e.g. in units of  $\text{¢/kWh}_{\text{out}}$ ) is:

$$\text{Sell Price} - (\text{Charging Energy Price} \div \text{Storage Efficiency}) - \text{O\&M} - \text{Replacement Cost.}$$

The annual net benefit assumed for arbitrage was evaluated using a simple model developed by DUA [1] that uses “perfect knowledge” about future prices to “look ahead,” to identify profitable sell opportunities. The dataset assumptions – comprised of 8,760 hourly price points, one for each hour of the year – is an electric energy price projection for California that was created by a production cost model.

Results shown in Figure 10 reflect *net benefit* for storage operated for one year. That is, they reflect the benefit remaining after accounting for the incremental cost for charging energy, energy losses, and variable operating cost (variable O&M and replacement costs).

Results are provided for storage systems whose variable operating cost (O&M and replacement cost per  $\text{kWh}_{\text{out}}$ ) ranges from: a) nothing, to b)  $1\text{¢/kWh}_{\text{out}}$ , and c)  $2\text{¢/kWh}_{\text{out}}$ . The data band shown for each cost scenario reflects net benefits for storage efficiencies ranging from 70% to 90% with storage discharge durations from one hour to eight hours.



**Figure 10.** Net Arbitrage Benefits, \$/kW.

## Central Generation Capacity Credit

The central generation capacity credit is estimated based on the premise that storage will be discharging during or close to peak demand periods and assuming a benefit that is based on the cost for a new peaker power plant. Based on the costs for several types of combustion turbine power plants, an installed cost of \$500/kW is assumed. [12] That installed cost is used with the 0.11 fixed charge rate described in Section 2 to estimate the annual first year benefit of  $\$500 * 0.11 = \$55/\text{kW-year}$ . Over ten years, that is a present worth of  $7.17 * \$55/\text{kW-year} = \$395/\text{kW}$ .

## Combined Benefits

The benefits for value proposition 3 are indicated in Figure 11.

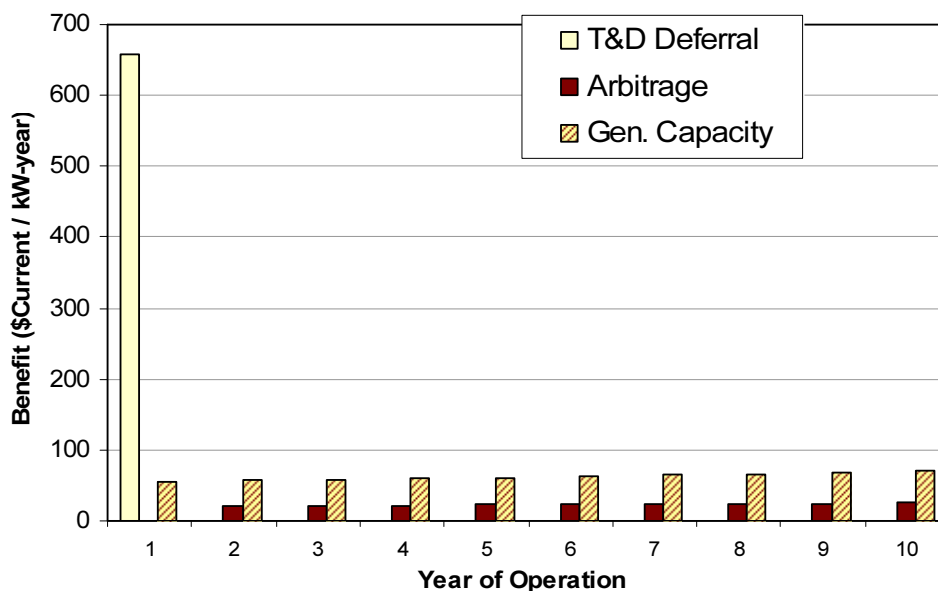
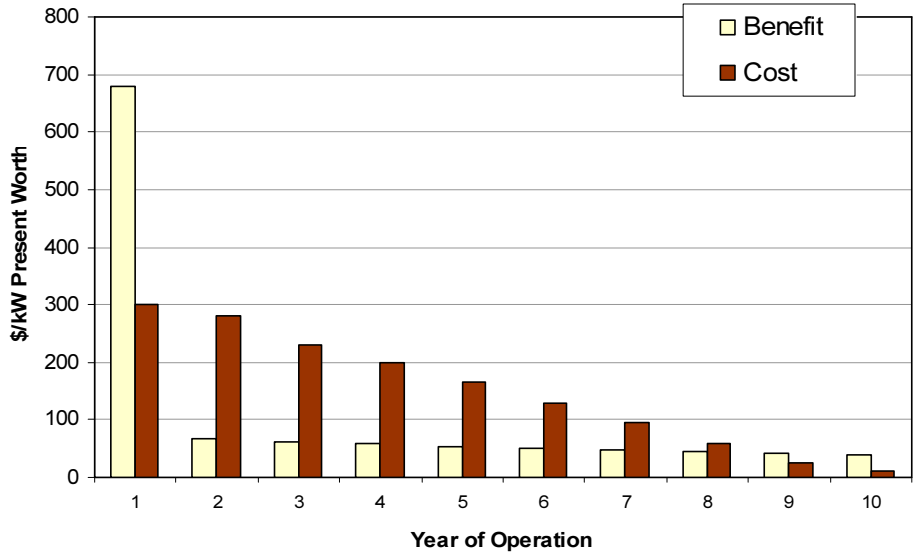


Figure 11. Present Worth of Benefits for Value Proposition 3.

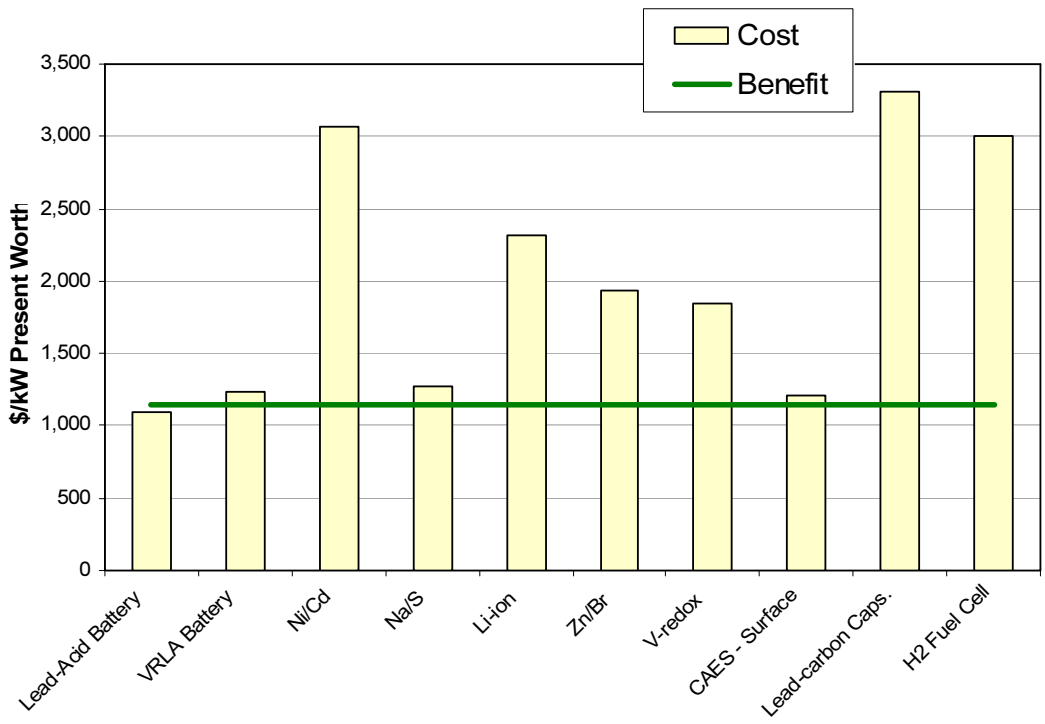
## Benefit/Cost Results

Annual benefit/cost results – reflecting cost and performance of the aforementioned state-of-the-art flooded lead-acid battery system – are shown in Figure 12.

Ten-year benefit / cost results for all storage technologies evaluated are shown in Figure 13. The state-of-the-art flooded lead-acid battery provides the highest benefit / cost, primarily because that technology has the lowest capital equipment cost.



**Figure 12. T&D Deferral, Arbitrage and Capacity Credit: Present Worth of Benefits and Cost for a flooded Lead-Acid Battery System.**



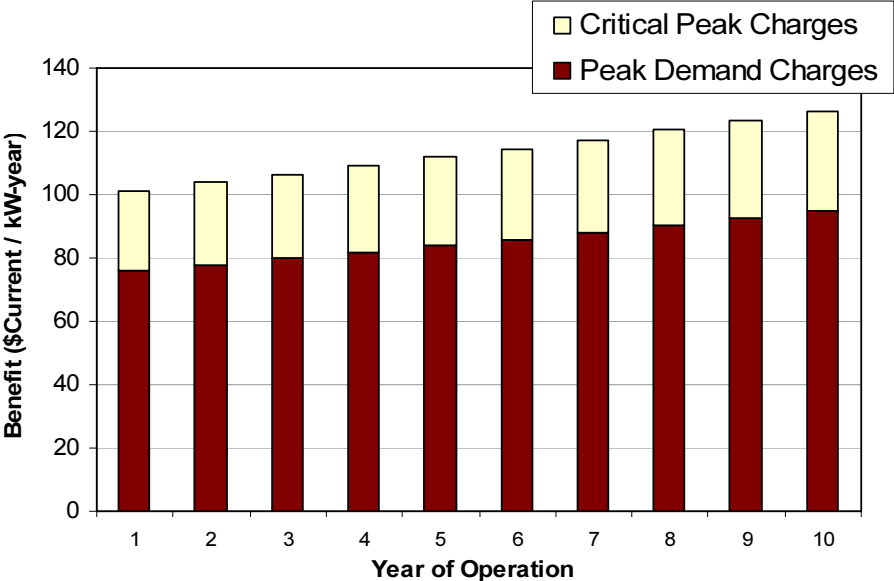
**Figure 13. T&D Deferral, Arbitrage and Capacity Credit: 10-year Present Worth of Benefits and Costs for Various Storage Technology Types.**

**Value Proposition 4: Peak and Critical Peak Electricity Pricing**

For this value proposition, a commercial electricity end-user’s utility cost is reduced by using storage during peak and critical peak times. As of late 2005, Pacific Gas and Electric Company (PG&E) was offering Critical Peak Pricing (CPP) to some customers. In this situation, a customer is offered a discount on electricity prices during “non-critical” times (e.g. when generation reserve margins are adequate). This offer is made if the customer agrees to pay “very high” prices during critical peak periods in return for the discount. These prices can be as high as 5 times the normal peak energy charge, and be expected to prevail several times per year (the PG&E target is 12 times/yr), for periods lasting from 3 to 6 hours per event. Thus, a customer might make such an agreement using energy storage.

**Benefit**

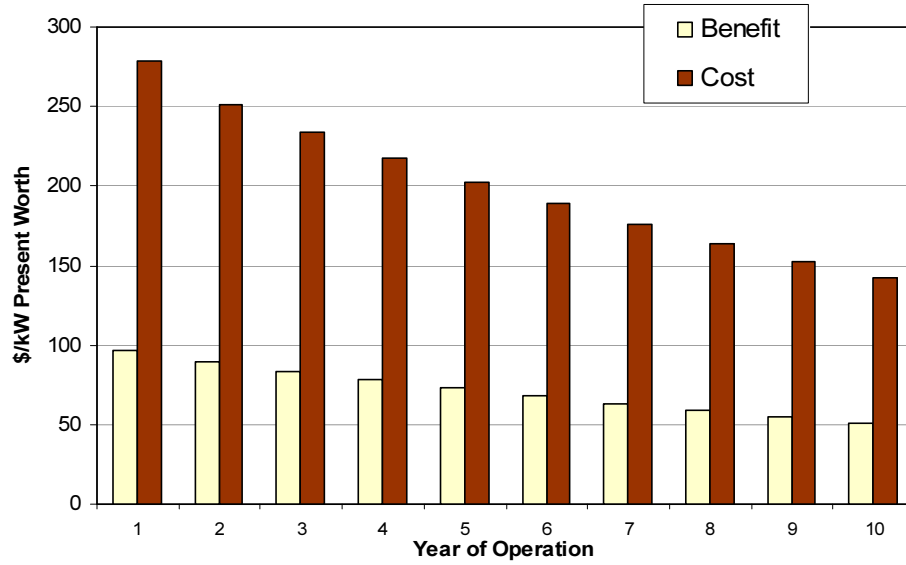
Critical peak and peak pricing benefits were calculated based on PG&E E19, Medium Commercial Rates. [11] The annual benefit due to CPP provisions for operation of 12 full 5-hr discharges per year (60 hrs) is estimated as \$25/kW per year. The annual benefit for operating storage during all peak-period price hours – including demand charge reduction – is \$100/kW per year. 1,600 hours per year of storage discharge is assumed. These values have been used to calculate benefits for the CPP value proposition. The annual benefits are shown in Figure 14.



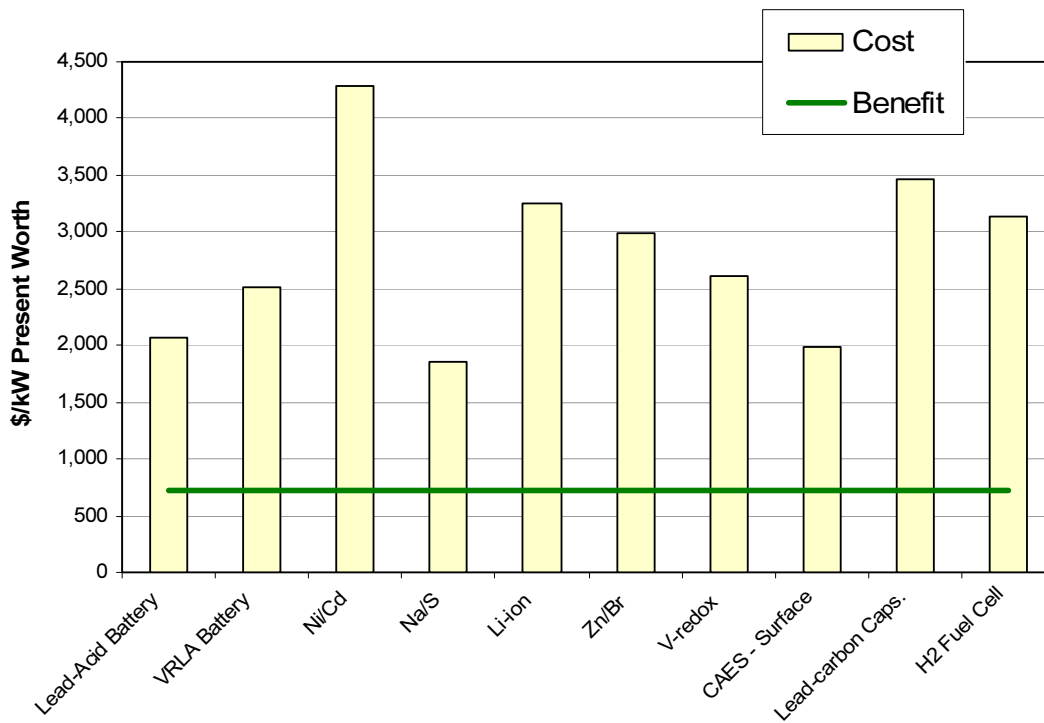
**Figure 14. Peak and Critical Peak Pricing Value Proposition; Annual Benefits (\$Current).**

**Benefit/Cost Results**

Results (present worth of benefits and costs) for a flooded lead-acid battery system operating in value proposition 4 are shown in Figure 15, for each of 10 years. Even using off-peak electricity costs, the benefits are insufficient to break even. As seen in Figure 16, none of the technologies evaluated has a cost that is commensurate with the benefit.



**Figure 15. Peak and Critical Peak Pricing Value Proposition: Present Worth of Annual Benefits and Costs for 5-hr flooded Lead-Acid Battery.**



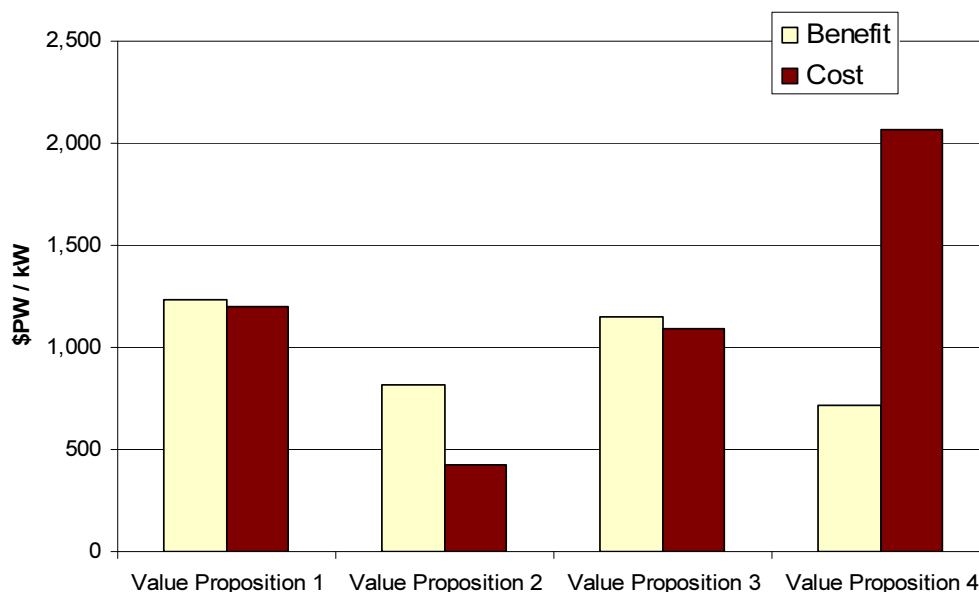
**Figure 16. Peak and Critical Peak Pricing Value Proposition: Present Worth of Benefits and Costs for Storage Technologies, 10-year Lifecycle.**



## 6. Conclusions and Recommendations

### Summary Results

Figure 17 shows the present worth of benefits and costs for lead-acid battery storage used for the four value propositions investigated. Most notably: value proposition 1 (T&D deferral plus PQ), value proposition 2 (PQ/reliability only) and value proposition 3 (high value T&D deferral plus arbitrage and generation capacity credit) show promise as they have a benefit/cost ratio greater than 1.



**Figure 17. 10-year Benefits and Costs for a flooded Lead-Acid Battery System for Value Propositions 1, 2, 3 and 4.**

### Conclusions

Four value propositions were evaluated using an analysis approach that compares costs and benefits on a common basis. Other value propositions may also be defined to show potential viable storage applications. In this study, given existing and expected price signals and the authors' estimates of benefits associated with value propositions 1, 3, and 4, the costs for most types of MES are somewhat or significantly higher than estimated benefits. An exception is the case of short duration storage for power quality only (value proposition 2).

Regarding the arbitrage benefit, results suggests that energy storage system variable operating cost – especially maintenance and replacement cost – must be quite low for arbitrage to be attractive. The challenge is that, even for regions with “high” energy prices, during *most* hours in the year, the wholesale energy price is determined by large power plants with low marginal cost. Those prices are just too low for profitable arbitraging during most hours of the year unless the variable operation cost (not related to charging energy) for storage is also low. Specifically, as shown in Figure 10, if the non-energy variable operating cost (O&M plus replacement) exceeds

$2\phi/\text{kWh}_{\text{out}}$ , then the annual net benefit is likely to be quite low. Importantly, the non-energy variable operating cost, even for the most cost-effective MES technologies, is likely to exceed  $2\phi/\text{kWh}_{\text{out}}$  for the foreseeable future.

Given the low benefit for arbitrage (relative to storage cost), the best prospects for energy storage – especially modular, distributed storage – are value propositions involving use of the MES as “capacity resources” that offset the need for other capital equipment.

For some energy storage technologies – those for which each discharge results in relatively significant equipment degradation, and thus high replacement costs – the best value propositions are those involving relatively few discharges.

Perhaps the best overall example of a good capacity-related value proposition is MES used to defer T&D upgrades. MES could also be used to augment the T&D system (e.g. for increased reliability and/or improved power quality), in lieu of other equipment, temporarily or permanently.

Of course, storage used for *local* capacity-related needs (i.e. T&D deferral or to improve power quality) can also provide regional benefits to the grid, including reduced demand for generation and transmission capacity, voltage support, reduced T&D  $I^2R$  energy losses, rapid response operating reserves, etc.

That leads to the most important conclusion of this study: the most compelling value propositions for modular energy storage will likely involve strategic aggregation of two or more benefits so that benefits exceed costs. Benefit aggregation is necessary because individual benefits, even in “high value” circumstances, are rarely as high as MES cost. Similarly, the need to aggregate numerous individual, often year-specific benefits to cover the relatively high lifecycle costs of storage makes transportability quite attractive.

### ***R&D Needs and Opportunities***

The authors have identified the following activities as potentially fruitful research addressing attractive value propositions for energy storage, especially modular energy storage:

- Identify and characterize three to five emerging value propositions for MES characterized by specific criteria: 1) degree to which the value proposition is viable given: a) existing market mechanisms and b) expected and emerging market mechanisms, 2) ability to reduce regional blackouts (e.g. by providing local VARs), 3) expected utility infrastructure needs, 4) increasing penetration of intermittent renewables, and 5) increasing interest in “demand response” resources.
- Identify key technical and institutional challenges affecting the prospects for otherwise cost-effective use of MES by utilities, electricity end users, load aggregators and other third party electricity services providers, and characterize specific ways to reduce those challenges.
- Given results indicating that flywheel energy storage may be cost-effective as a transportable power quality resource, further investigation of that value proposition for flywheels is warranted.

## Terms Used in this Document

**Demand** – The rate of electric energy delivery, normally in units of kilowatts (kW) or megawatts (MW) for utilities (not adjusted for power factor).

**Direct Cost** – All direct costs to own or to rent an option, possibly including some or all of the following: rental charges, equipment purchase and delivery cost, project design, installation, depreciation, interest, dividends, taxes, service, consumables, fees and permits, and insurance. Direct cost reflects “point estimates” of future values, without regard to uncertainty.

**Distribution** – See Electricity Distribution

**Electricity Distribution** – Electricity distribution is part of the electricity grid that delivers electricity to end-users. It is connected to the transmission system which, in turn, is connected to the electric supply system (generators). Relative to electricity *transmission*, the distribution system is used to send relatively small amounts of electricity over relatively short distances. In the U.S., distribution system operating voltages generally range from several hundred volts to 50kV (50,000 Volts). Typical power transfer capacities range from a few tens of MWs for substation transformers to tens of kilowatts for small circuits.

**Electricity Subtransmission** – As the name implies, subtransmission transfers smaller amounts of electricity, at lower operating voltages than transmission. For the purposes of this study, “transmission and distribution” is assumed to include subtransmission and not high capacity/high voltage transmission systems.

**Electricity Transmission** – Electricity transmission is the “backbone” of the electricity grid. Transmission wires, transformers, and control systems transfer electricity from supply sources (generation or electricity storage) to utility *distribution* systems. Relative to electricity *distribution* systems, the transmission system is used to send large amounts of electricity over relatively long distances. In the U.S., transmission system operating voltages generally range from 200 kV (200,000 Volts) to 500 kV. Transmission systems typically transfer the equivalent of 200 to 500 megawatts of power. Most transmission systems use alternating current though some larger, longer transmission corridors employ high voltage direct current.

**Equipment Rating** – The amount of power that can be delivered under specified conditions. The most basic rating is the “nameplate” rating: nominal power delivery rate under “design conditions.” Other ratings may be used as well. For example, T&D equipment often has what is commonly called an “emergency” rating. That is the sustainable power delivery rate under “emergency conditions” such as when load exceeds nameplate rating by several percentage points. Operation at emergency rating is assumed to occur infrequently, if ever.

**Peak Demand** – The maximum power draw on a power delivery system, usually year-specific.

**Subtransmission** – See Electricity Subtransmission

**Value Proposition** – A value proposition is comprised of all benefits and all costs, including risk, that are associated with an investment or purchase.



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