Analysis of the Cost per Kilowatt Hour to Store Electricity

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***Abstract*—This paper presents a cost analysis of grid-connected electric energy storage. Various energy storage technologies are considered in the analysis. Life-cycle cost analysis is used. The results are presented in terms of the cost added to electricity stored and discharged, in US dollar per kilowatt hour. Results are compared with wholesale and retail electricity costs and with the cost of conventional pumped hydro storage.**

***Index Terms*—Batteries, economic analysis, energy storage, flywheels.**

NOMENCLATURE

A	Annual storage unit replacement cost (US$/kWh).
AC	Annualized capital cost (US$/year).
AEP	Annual energy production of storage system (kWh/year).
ARC	Total annual replacement cost (US$/year).
BOP	Total cost for balance of plant (US$).
BOPU	Unit cost for balance of plant (US$/kWh).
C	Number of charge/discharge cycles in life of storage.
COE	Cost added by storing electricity (US$/kWh).
CRF	Capital recovery factor.
D	Annual operating days for storage unit (days per year).
eff	Efficiency
F	Future value of replacement cost (US$/kWh).
H_{O}	Length of each discharge cycle (h).
i_r	Annual interest rate (%).
n	Number of charge/discharge cycles per day.
OM_f	Fixed operation and maintenance cost (US$/kW·year).
OMC	Total annual fixed operation and maintenance cost (US$/year).
P	Rated power output capacity of energy storage system (kW).
PCS	Total cost for power electronic (US$).
PCSU	Unit cost for power electronic (US$/kW).
r	Replacement period (year).
SUC	Total cost for storage units (US$).
SUCU	Unit cost for storage units (US$/kWh).
TCC	Total capital cost (US$).
y	Lifetime of energy storage (year).

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I. INTRODUCTION

THERE are about 90 GW of electric energy storage, almost all pumped hydro, operating in the world today [1], which is 3% of total generating capacity. New pumped hydro installations are limited by availability of sites. Siting concerns are reduced if other storage technologies are located in smaller units on the distribution system. This concept is known as distributed energy storage (DES).

The DES may, in the future, be more important, and be present in much higher penetrations than distributed generation (DG) [2]. The DES technologies may include batteries, flywheels, and electrochemical capacitors (“super” or “ultra” capacitors), of which batteries and flywheels appear to be the most promising for bulk storage. Compressed air energy storage and pumped hydro storage are usually large and have special siting needs, and superconducting magnetic energy storage are short-duration devices used for uninterruptible power supplies and other power quality support, making them less suitable for the DES.

The benefits of electricity storage are well known and include the following [2]:

1) *Support of renewables:* Storage can reduce fluctuations in wind and photovoltaic (PV) output, and allows sale of renewable energy at high-value times.
2) *Reliability and power quality:* Storage will allow loads to operate through outages.
3) *Reactive power control, power factor correction, and voltage control:* Power electronic interfaces provide the ability to rapidly vary reactive as well as active power.
4) *Load leveling:* Storage is charged during light-load periods, using low-cost energy from base-load plants, and discharged during high-load times, when the energy value is higher. The benefits are improved load factor, deferred generation expansion, and reduced purchase at peak times and generation by peaking units.
5) *Load following:* Storage with power electronic interfaces can follow load changes very rapidly, reducing the need for generating units to follow load.
6) *Bulk energy management:* Bulk power transfers can be delayed by storing the energy until it is needed, or until its value increases.
7) *Spinning reserve:* Because of its ability to rapidly change the output, storage with power electronic interfaces can act as spinning reserve, reducing the need for conventional spinning reserve units.

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8) *Deferral of new transmission capacity:* Properly located storage units can be charged during off-peak times, reducing peak loading of transmission lines and effectively increasing transmission capacity.
9) *Deferral of new generating capacity:* Fewer peaking units are needed when storage reduces peak demand.
10) *Support of distributed generation:* Storage allows the DG, such as microturbines and fuel cells, to be operated at constant output at its highest efficiency, reducing fuel use and emissions. Discharging DES during peak demand times also reduces the needed capacity of the DG.
11) *System stability:* Power and frequency oscillations can be damped by rapidly varying the real and reactive output of storage. The improved stability margin is obtained by electronic controls for the DES.
12) *Automatic generation control:* Energy stored on a system can be used to minimize area control error. The benefits are easier compliance with North American Electric Reliability Corporation (NERC) standards (C1–C4) and reduced mechanical wear on cycling units.
13) *Black start capability:* Stored energy can be used to start an isolated generating unit.
14) *Reduced fuel use:* Use of less-efficient peaking units is reduced by charging storage with energy from more-efficient base load-generating units. Because peaking units often burn natural gas, this also offers natural gas conservation benefits. Also, by improving the system power factor, losses will be reduced, and there is a concomitant reduction of energy use.
15) *Environmental benefits:* Reduced fuel use results in reduced emissions and natural gas conservation.
16) *Increased efficiency and reduced maintenance of generating units:* Load following by storage units allows prime movers to be operated at more constant and efficient set points, increasing their efficiency, maintenance intervals, and useful life.
17) *Increased availability of generating units:* During peak periods, charged energy storage added to available generation increases total system capacity.

While electricity storage is understood to have these strong technical merits, it is generally thought of as too expensive to be used in high penetrations. The costs of storage technologies, however, are dropping, and cost/benefit analyses have shown that it is economically justified in some cases [3].

This paper presents the development of a new technique for a simple economic feasibility evaluation of small energy storage facilities. Such facilities would be used, for example, for renewable energy or distributed storage. The technique calculates the cost added to each unit of energy [in kilowatt hour (kWh)] that is stored, and later, returned to the grid.

Results for several commercially available types of energy storage, including conventional pumped hydro, are, then, presented. The results are compared with existing and forecast electricity prices, and other issues that might affect the feasibility of small storage units are discussed. Conclusions are, then, presented on the possible future use of small energy storage systems.

II. Distributed Energy Storage Costs

There are two costs to consider for an electricity storage system. The energy cost is the cost of storage elements, e.g., pumped hydro reservoirs or batteries. The energy cost is expressed in cost per unit of stored energy, US$ per kilowatt hour, for example. This is not to be confused with the conventional cost of purchasing a unit of electricity, which has identical units. The energy cost for storage is the cost of the devices that actually store the energy, which can be charged and discharged many times. The energy rating of a storage system is the total energy that the system can store.

The other cost of energy storage is the power cost. This would include the rotating synchronous machines in a pumped hydro unit, or the power electronic rectifier/inverters in a battery storage system. The power cost is expressed in cost per unit of power, US$ per kW, for example. The power rating is the instantaneous capacity of the storage unit. It determines how quickly the storage system can be charged or discharged. The two costs, power and energy, in combine, give the total initial capital cost of a storage unit.

The economics of large pumped hydro units are analyzed with production costing techniques. For smaller applications such as flywheels, battery energy storage units, DG, and renewable energy applications, it is useful to have a simpler technique of estimating the economics of storage units. One such method is to convert the energy, power, installation, and operating and maintenance costs of a storage unit to the cost added to a unit of electricity stored. This cost is, then, added to the conventional electricity price to determine a total price for stored electricity. For example, if electricity is generated at US$0.05/kWh, and a particular storage system adds US$0.10/kWh, then, the total price of that unit of stored electricity is US$(0.05 + 0.10)/kWh = US$0.15/kWh. This can, then, be compared with potential additional value of storing electricity, such as shifting wind-generated electricity from off- to on-peak, for an initial estimate of the feasibility of energy storage.

This paper presents a technique to convert the installed and annual costs of energy storage to the cost added to each stored unit of electricity. The technique was developed for applications such as distributed storage and renewable energy. The most promising technologies for such applications are flywheels and various types of batteries. All use a power electronic rectifier–inverter interface, so that the technique assumes such an interface.

III. Calculation of Cost Added to Store Electricity

The total energy discharged annually by an energy storage system is referred to as annual energy production (AEP), which can be written as

$$\mathrm{AEP} = P^* n^* H_0{}^* D. \tag{1}$$

The annual fixed operation and maintenance cost in US$ per year is

$$\mathrm{OMC} = \mathrm{OM}_f{}^* P. \tag{2}$$

The TCC for the energy storage system consists of three components: the total (power) cost of power electronic rectifier/

inverters, the total (energy) cost for storage units, and the TCC for the balance of plant.

The total cost for the power electronics in US$ is

$$\mathrm{PCS} = \mathrm{PCSU}^{*} P. \quad (3)$$

The total cost for storage units in US$ can be obtained by

$$\mathrm{SUC} = \frac{\mathrm{SUCU}^{*} P^{*} H_{\mathrm{O}}}{\mathrm{eff}} \quad (4)$$

$$\mathrm{eff} = \frac{\mathrm{energy\_(kWh)\_out\_during\_discharge}}{\mathrm{energy\_(kWh)\_in\_during\_charge}}. \quad (5)$$

The total cost for the balance of plant in US$ is

$$\mathrm{BOP} = \mathrm{BOPU}^{*} P^{*} H_{0}. \quad (6)$$

The TCC, which is the sum of the total costs for the power electronics, storage units, and balance of plant, is

$$\mathrm{TCC} = \mathrm{PCS} + \mathrm{SUC} + \mathrm{BOP}. \quad (7)$$

The annualized capital cost is, then,

$$\mathrm{AC} = \mathrm{TCC}^{*}\mathrm{CRF}. \quad (8)$$

The CRF [4] is given as

$$\mathrm{CRF} = \frac{i_r (1+i_r)^y}{(1+i_r)^y - 1}. \quad (9)$$

When batteries are used as the storage element, they may have to be replaced one or more times during the life of the plant. This cost is annualized (US$ per kilowatt hour) [4] as

$$A = F^{*}[(1+i_r)^{-r} + (1+i_r)^{-2r} + \cdots]^{*}\mathrm{CRF}. \quad (10)$$

The number of terms in the factor of the previous equation is equal to the number of times batteries are replaced during the life of the system. Thus, the equation shown, with two terms, is for batteries being replaced twice during the plant life.

Battery life is the fixed number of charge/discharge cycles. The replacement period in years can, then, be calculated as follows

$$r = \frac{C}{n^{*} D}. \quad (11)$$

The annual battery replacement cost, then, is

$$\mathrm{ARC} = \frac{A^{*} P^{*} H_{\mathrm{o}}}{\mathrm{eff}}. \quad (12)$$

Finally, the cost added to a unit (in kilowatt hour) of electricity stored is

$$\mathrm{COE} = \frac{(\mathrm{AC} + \mathrm{OMC} + \mathrm{ARC})}{(P^{*} n^{*} H_{\mathrm{O}}{}^{*} D)}. \quad (13)$$

Table I summarizes the inputs needed to do these calculations and the outputs of the calculations.

TABLE I
INPUTS AND OUTPUTS OF THE CALCULATIONS

Inputs
Rated output (kW)
Number of charge/discharge cycles per day
Length of each discharge cycle (h)
Annual operating days (day/yr)
Unit cost for power electronic (US$/kW)
Unit cost for storage units (US$/kWh)
Unit cost for balance of plant (US$/kWh)
Efficiency
Interest rate (%)
Fixed operation and maintenance cost (US$/kW)
Future amount of replacement cost (US$/kWh)
Number of charge/discharge operation cycles in life

Outputs
Rated energy capacity (kWh)
Rated storage capacity (kWh)
Capital recovery factor
Replacement period (yr)
Total cost for power electronic interface (US$)
Total cost for storage units (US$)
Total cost for balance of plant (US$)
Annual capital cost (US$/yr)
Annual fixed O&M cost (US$/yr)
Annual replacement cost (US$/yr)
Annual energy production (kWh/yr)
Cost added to the unit of energy stored (US$/kWh)

IV. Case Studies

A. Assumptions

In the case studies presented in this section, systems are assumed to operate either 250 or 100 d/year. Systems operating all year will operate about 250 d/year, the approximate number of weekdays minus holidays in a year. Systems designed to operate only during peak use seasons are assumed to operate 100 days, or 20 weeks, per year.

The length of the discharge cycle depends on the application. In this paper, 8 h [5] is assumed for generation applications. Generation applications are designed to charge overnight and discharge during the day. Thus, storage for generation is assumed to charge and discharge one time during each 24-h period. For transmission and distribution (T&D) applications, storage discharges during morning and afternoon peak periods and is charged at other times. A 4 h [5] discharge time is assumed for T&D storage systems, and these systems charge and discharge twice during each 24-h period.

Rated output capacity for generation applications ranges from 10 to 1000 MW [5]. Capacity for transmission/distribution applications is between 100 kW and 2 MW [5].

This paper assumes that the annual interest rate for financing the storage system is 7.7% [6]. Inflation and escalation rates are not considered in this analysis.

B. Storage Systems and Technologies

The most promising commercial or near-commercial battery technologies are considered in this analysis: lead acid (LA), valve-regulated LA (VRLA), sodium sulfur (Na/S), zinc/bromine (Zn/Br), and vanadium redox (VB). Flywheels, which are commercially available for power quality applications and are now being demonstrated for frequency regulation [7], are the most promising nonbattery storage technology, and these are also considered for T&D applications.

TABLE II
ADJUSTED CASE VALUES FOR GENERATION APPLICATIONS [5], [8]

Parameters	LA	VRLA	Na/S	Pumped Hydro	VB
Rated output (kW)	10000	10000	10000	10000	10000
Efficiency	0.75	0.75	0.77	0.75	0.7
Unit cost for power electronic (US$/kW)	125	125	833	1000	(SEE NOTE)
Unit cost for storage units (US$/kWh)	305	360	208	10	500
Unit cost for balance of plant (US$/kWh)	150	150	0	4	30
Fixed O&M cost (US$/kW)	15	5	20	2.5	20
Future amount of replacement cost (US$/kWh)	305	360	208	0	150
Number of charge/ discharge cycles in life	3200	1000	2500	N/A	10000
NOTE— Unit cost for power electronic of VB is included in unit cost for storage units.					

TABLE III
ADJUSTED CASE VALUES FOR T&D APPLICATIONS [5], [8]

Parameters	LA	VRLA	Na/S	Zn/Br	Fly-wheel	VB
Rated output (kW)	2500	2500	2500	2500	2500	2500
Efficiency	0.75	0.75	0.77	0.7	0.95	0.7
Unit cost for power electronic (US$/kW)	175	175	1000	175	300	(SEE NOTE)
Unit cost for storage units (US$/kWh)	305	360	500	225	1000	740
Unit cost for balance of plant (US$/kWh)	50	50	0	0	0	30
Fixed O&M cost (US$/kW)	15	5	20	20	$1000 /yr	20
Future amount of replacement cost (US$/kWh)	305	360	500	225	0	222
Number of charge/ discharge cycles in life	3200	1000	2500	10000	N/A	10000
NOTE— Unit cost for power electronic of VB is included in unit cost for storage units.						

These storage technologies are all commercially available. Manufacturers of each provided price quotes and performance information in 2007 for bulk storage applications. These 2007 prices are presented in Tables II and III. Table II shows the data for generation applications, and Table III presents the values for T&D applications.

V. RESULTS

The technique developed in Section III of this paper is applied to the case study values and assumptions from Section IV. The resulting costs, which are the costs added by the various storage technologies to each kilowatt hour of electricity that is stored,

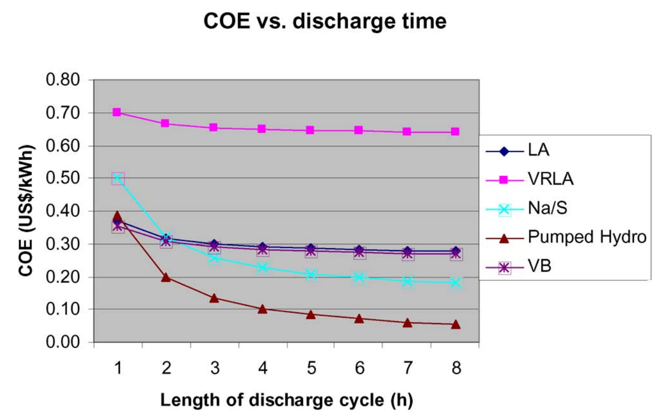


Fig. 1. Added cost (COE) vs. discharge time, 10 MW generation application operating 250 d/year.

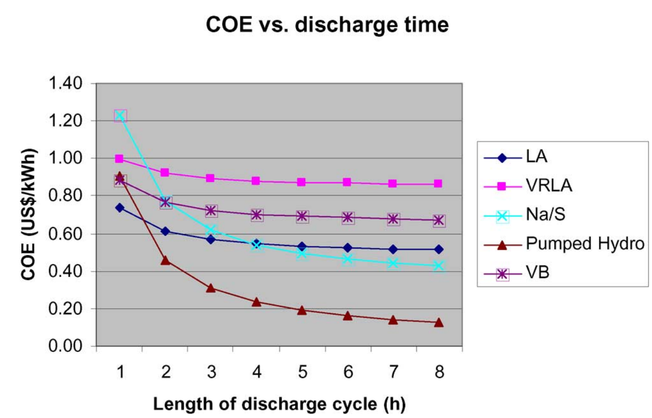


Fig. 2. Added cost (COE) vs. discharge time, 10 MW generation application operating 100 d/year.

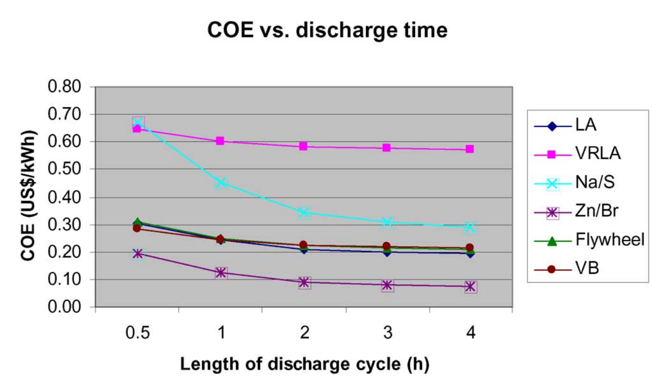


Fig. 3. Added cost (COE) vs. discharge time, 2.5 MW T&D application operating 250 d/year.

are plotted in Figs. 1–4. Each figure shows the cost added as the actual charge/discharge times are varied. For generation applications (see Figs. 1 and 2), the systems are designed for 8 h discharge, and thus, the lowest cost is seen at 8 h, because at shorter times, available capacity goes unused. Similarly, Figs. 3 and 4 are for T&D applications, designed for 4 h discharge time, and the lowest cost is at 4 h.

The data for generation applications are for systems operating year-round (250 d/year, Fig. 1), and operating only during the

TABLE IV
COST ADDED TO COST OF ELECTRICITY USING SYSTEM AS DESIGNED

System design	Cost added (US$/kWh)
Generation, 250 days/yr (batteries)	0.18-0.64
Generation, 250 days/yr (pumped hydro)	0.05
Generation, 100 days/yr (batteries)	0.42-0.86
Generation, 100 days/yr (pumped hydro)	0.12
T&D, 250 days/yr (batteries and flywheel)	0.07-0.57
T&D, 100 days/yr (batteries and flywheel)	0.20-0.64

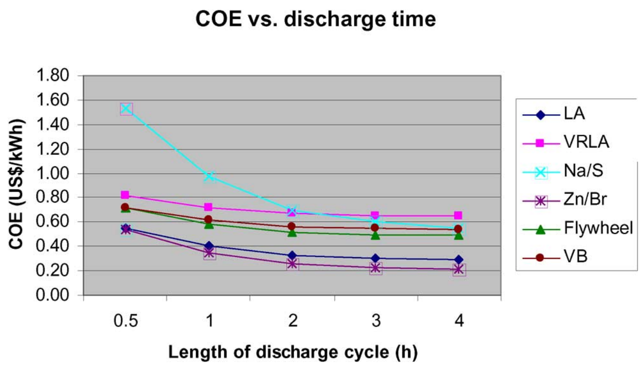


Fig. 4. Added cost (COE) vs. discharge time, 2.5 MW T&D application operating 100 d/year.

peak summer season (100 d/year, Fig. 2). Cost are substantially higher for systems operating only part of the year, because the system fixed costs are spread over a much lower number of total kilowatt hour stored.

Data are also presented for T&D applications operating 250 d/year (see Fig. 3) and 100 d/year (see Fig. 4). Higher costs are seen, similar to generation results, for the systems operating fewer days per year.

Cost for battery generation applications are increased relative to T&D applications because of the difference in storage time. The same number of total kilowatt hour is stored each day by each kilowatt of generation or T&D storage capacity, but the generation system needs twice the energy storage:

$$\begin{array}{ll} \text{Generation:} & 1\ \text{kW} \times 8\ \text{h} \times 1\ \text{cycle/d} = 8\ \text{kWh/d} \\ & \text{Energy rating: } 8\ \text{kWh} \\ \text{T\&D:} & 1\ \text{kW} \times 4\ \text{h} \times 2\ \text{cycles/d} = 8\ \text{kWh/d} \\ & \text{Energy rating: } 4\ \text{kWh.} \end{array}$$

The T&D storage system cost, however, is increased by more frequent replacement of batteries. Battery life is measured in charge/discharge cycles; so, the life, converted to years, of a battery in T&D service will be half that of a battery in generation service. For example, a battery with 1500 cycle life:

$$\begin{array}{ll} \text{Generation:} & 1500\ \text{cycles/1 cycle/d} = 1500\ \text{d} \\ \text{T\&D:} & 1500\ \text{cycles/2 cycles/d} = 750\ \text{d.} \end{array}$$

Table IV summarizes the results for all systems operating as designed.

VI. INTERPRETATION OF RESULTS

With installed capacity equal to 3% of the total installed electric generating capacity in the world, pumped hydro storage, and its added cost to electricity of US$0.05/kWh, can be considered economically feasible for many applications. Indeed, many more pumped hydro units would be built if there were suitable locations for them; pumped hydro is limited to those sites with locations for two large reservoirs at significantly different heights.

TABLE V
US ELECTRICITY PRICES

Conditions	Electricity rate (US$/kWh)
Wholesale day ahead peak	0.1800 [9]
Average US Retail, Industrial	0.0573 [10]
Average US Retail, Commercial	0.0867 [10]
Average US Retail, Residential	0.0945 [10]

For battery and flywheel systems operating 250 d/year, Table IV shows that at the present day prices, such systems can store energy for about 3–12 times the cost of pumped hydro. The costs for systems operating 100 d/year are three–seven times the cost of pumped hydro.

Table V presents recent values for peak wholesale and average retail electricity prices in the US [9], [10]. Pumped hydro's added US$0.05/kWh cost is less than one-third of the wholesale peak, and almost equal to the average industrial retail price. The lowest cost battery system studied adds a cost to electricity approximately equal to the average retail price, while the highest cost system adds a cost of four times the wholesale peak price. Energy generated or purchased off-peak, when prices are lower, stored in a pumped hydro system, and used at peak times, will have a total price less than the peak purchase price. This is probably not yet the case with battery and flywheel systems. If prices in the US, however, were not capped, the wholesale peak price would be much higher, and other storage technologies would be more feasible. In Australia, for example, wholesale prices are capped at AU$10/kWh.

VII. CONCLUSION

A battery storage system designed to operate 250 d/year with one 8 h charge/discharge cycle per day adds US$0.18–0.64 to the cost of electricity at 2006 prices. A system that charges and discharges twice a day on a 4 h cycle adds about US$0.07–0.57. The lowest value is less than recent US wholesale peak prices and comparable to recent US average retail electricity prices. The high value is much higher than average wholesale or retail prices. Such costs will be justified for some applications, but difficult to justify for many others.

Similarly, a battery storage system designed to operate only during peak seasons, 100 d/year, on one 8 h cycle, adds US$0.42–0.86 to each kilowatt hour stored. A system that charges and discharges twice a day on a 4 h cycle adds about US$0.20–0.64 to each kilowatt hour stored.

These costs are between 3 and 12 times the cost of conventional pumped hydro storage. Pumped hydro capacity now equals 3% of the total world generating capacity, evidence of its economic viability. Suitable sites for new pumped hydro facilities are, however, limited. If the costs of battery and flywheel technologies continue to decrease, then, their operating costs will someday approach that of new pumped hydro.

If wholesale electricity price caps in the US are raised or removed, those prices at times will be many times higher than they are today. Storage of low-cost off-peak energy for use at on-peak times would become more economical because of the higher savings achieved.

Twenty-two US states have passed renewable portfolio standards [11] and more are enacted each year. Wind and solar generation produce only when the resource is available, which may not be when the electricity is needed. This makes penetrations exceeding 10%–15% impractical [12]. Storage allows the energy to be used when needed, allowing higher penetrations of renewables and greatly increasing the value of renewable energy generated off-peak.

From the comparison with wholesale electricity prices, it appears that the cost of electricity storage systems needs to drop significantly before it will be useful for widespread load-leveling use. Additional cost of energy, however, is only one component of the economic justification for storage. Other issues, such as deferral of transmission and generation facilities, and all others listed in Section I must be considered in a complete economic analysis. Market design and how markets will treat stored energy must also be considered.

The costs added to stored electricity are highly dependent on the system's design parameters: number of discharge cycles per day and number of operating days per year. Deviation in operation from design values, as indicated by the high (left end) values in Figs. 1–4, greatly increases operating costs. Great care should be taken in designing such systems to optimize operating costs.

Replacement period of batteries also has a crucial effect on stored energy costs. The system design should insure that the replacement period is proportional to the life of the power electronic (power conversion system) and balance of plant. Operation and maintenance costs are much less significant than capital and replacement costs.

The technique used to evaluate storage costs in this paper was implemented in a spreadsheet, which is available from the authors.

REFERENCES

[1] *Pumped Hydro Storage*. (2006). Electricity Storage Association, [Online]. Available: http://www.electricitystorage.org/tech/technologies_technologies_pumpedhydro.htm

[2] W. Jewell, P. Gomatom, L. Bam, and R. Kharel. (Jul. 2004). *Evaluation of Distributed Electric Energy Storage and Generation*, Final Report for PSERC Project T-21. PSERC Publication 04–25, *Power Syst. Eng. Res. Center* [Online]. Available: www.pserc.org/cgi-pserc/getbig/publicatio/reports/2004report/jewell_der_final_report_2004.pdf

[3] *EPRI-DOE Handbook of Energy Storage for Transmission and Distribution Applications, EPRI*, 2003.

[4] M. R. Lindberg, "Engineering economic analysis," in *Mechanical Engineering Review Manual*, 8th ed. San Carlos, CA: Professional Publications, 1990, ch. 2, pp. 2–3.

[5] S. M. Schoenung and W. V. Hassenzahl, "Long- vs. short-term energy storage technologies analysis: A life-cycle cost study," *Sandia Natl. Lab.*, Albuquerque, NM, Sandia Rep. SAND2003-2783, 2003.

[6] Energy Information Administration (2006). Annual energy outlook 2006 with projection to 2030. Report No. DOE/EIA-0383. [Online]. Available: http://www.eia.doe.gov/oiaf/aeo/

[7] S. Blankenship, "Flywheel prototype to be demonstrated for frequency regulation/grid stability," *Power Eng.*, vol. 109, no. 4, p. 46, Apr. 2005.

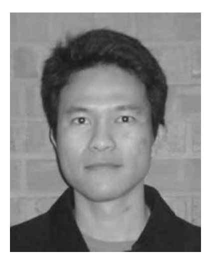
[8] Information from price quotes and performance data provided by energy storage device manufacturers.

[9] Energy Information Administration (Nov. 2006). Wholesale day ahead prices at selected hubs, peak. [Online]. Available: http://www.eia.doe.gov/cneaf/electricity/wholesale/wholesale.html

[10] Energy Information Administration (Oct. 2006). "Average Retail Price of Electricity to Ultimate Customers by End-Use Sector," Electric Power Annual with data for 2005. [Online]. Available: http://www.eig.gov/cneaf/electricity/epa/epat7p4.html

[11] States with Renewable Portfolio Standards (May 2006). Pew center on global climate change. [Online]. Available: www.pewclimate.org/what_s_being_done/in_the_states/rps.cfm

[12] W. Jewell, R. Ramakumar, and S. Hill, "A study of dispersed photovoltaic generation on the PSO system," *IEEE Trans. Energy Convers.*, vol. 3, no. 3, pp. 473–478, Sep. 1988.



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