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Analysis of the Value of Battery Storage with Wind and Photovoltaic Generation to the Sacramento Municipal Utility District

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Analysis of the Value of Battery Storage with Wind and Photovoltaic Generation to the Sacramento Municipal Utility District*

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Abstract

The U.S. Department of Energy's Energy Storage Systems Program at Sandia National Laboratories funded a study to determine the economic and operational value of battery storage to wind and photovoltaic technologies on the Sacramento Municipal Utility District system. This report presents the performance predictions and preliminary benefit-cost results for battery storage added to the Solano wind plant and the Hedge photovoltaic plant.

* The work described in this report was performed for Sandia National Laboratories under Contract No. AV-5094.

Acknowledgments

Sandia National Laboratories would like to acknowledge and thank the U.S. Department of Energy's Office of Utility Technologies for the support and funding of this work. We would like to acknowledge the Sacramento Municipal Utility District's operating, planning and design personnel for providing extensive access to the District's planning and resource information and reports, which contributed to the data and assumptions upon which this analysis is based. Sandia staff member Abbes Akhil is recognized for providing initial guidance and planning for this analysis. Thanks are also due to Paul Butler from Sandia's Energy Storage Analysis and Development Department for providing valuable technical review prior to publication.

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Acronyms

ACE	area control error
O&M	operation and maintenance
PG&E	Pacific Gas and Electric
PSA	Power Service Agreement
PV	photovoltaic
PWRR	present worth of revenue requirement
SMUD	Sacramento Municipal Utility District
SNL	Sandia National Laboratories
T&D	transmission and distribution

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1. Introduction

This report describes the results of an analysis to determine the economic and operational value of battery storage to wind and photovoltaic (PV) generation technologies to the Sacramento Municipal Utility District (SMUD) system.

This project was jointly funded by SMUD and Sandia National Laboratories (SNL). The project scope consisted of performing the following work:

- Identify two sites for potential installation of battery energy storage on the SMUD system. One site will service a PV system, and the second will service the SMUD Solano wind project.

- Quantify the costs and benefits of batteries when used in each of these applications. Major emphasis will be placed on assessing the capability of battery energy storage to enhance the variable outputs of PV systems and wind plants.

The analysis approach consisted of performing a benefit-cost economic assessment using established SMUD financial parameters, system expansion plans, and current system operating procedures.

The work was completed in early 1995 and consisted of the following tasks:

- Screen battery benefits and gather SMUD data;

- Select appropriate wind and PV plant sites;

- Identify potential battery storage benefits;

- Perform preliminary battery storage benefit-cost assessment;

- Obtain battery storage cost estimates from manufacturers; and

- Prepare report.

This report presents the results of the analysis. Section 2 describes expected wind and PV plant performance. Section 3 describes expected benefits to SMUD associated with employing battery storage. Section 4 presents preliminary benefit-cost results for battery storage added at the Solano wind plant and the Hedge PV plant. Section 5 presents conclusions and recommendations resulting from this analysis.

The results of this analysis should be reviewed subject to the following caveat. The assumptions and data used in developing these results were based on reports available from and interaction with appropriate SMUD operating, planning, and design personnel in 1994 and early 1995 and are compatible with financial assumptions and system expansion plans as of that time. Assumptions and SMUD expansion plans have changed since then. In particular, SMUD did not install the additional 45 MW of wind that was planned for 1996. Current SMUD expansion plans and assumptions should be obtained from appropriate SMUD personnel.

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2. Wind and Photovoltaic Plant Performance

This section describes wind plant and PV plant electrical performance data collected as part of this analysis.

Solano 5-MW Wind Plant Performance

Monthly capacity factors for the Solano 5-MW wind plant from July through December 1994 are summarized in Table 2-1. Energy production is highest in the summer months and lowest in the winter months.

Table 2-1. Monthly Solano Wind Plant Capacity Factors

July 1994	69.5%
August 1994	46.3%
September 1994	38.9%
October 1994	21.0%
November 1994	12.4%
December 1994	3.8%

The total aggregated output for July 1994 through December 1994 of the 17 turbines that make up the 5-MW Solano wind plant is shown in Figures 2-1 through 2-6. These figures illustrate the nature of wind plant output. In some hours, the wind plant output can exceed the 5-MW, wind-plant nameplate capacity. For example, Figure 2-7 presents a plot of the hourly integrated kilowatt wind plant output exceeding the 5-MW, wind-plant capacity rating during July 1994. In July, the wind-plant hourly output exceeded 5 MW over 20 times, sometimes by as much as 300 kW, or 6%. The wind plant output also exceeded 5 MW in other months. On the other hand, wind plant output is zero in many other hours, even during peak wind resource months.

In SMUD's 1993 *Integrated Resource Plan Update*,[1] wind plants were assigned a 0% capacity factor for planning purposes. As of 1994, conversations with SMUD personnel indicated that wind plants were being assigned a 15% capacity factor in the latest draft of the 1995 *Integrated Resource Plan Update*.[2] The basis for the 15% capacity factor was other utility studies showing that wind plants provide some degree of increased reliability. For example, Southern California Edison assigned a 25% capacity factor to wind in the early 1990s.

The peak load of the daily SMUD system load shape generally occurs around 6:00 p.m. Pacific daylight time during the peak load months of July and August. The 6:00 p.m. aggregated kW output for July and August 1994 of the 17 turbines that make up the Solano wind plant is shown in Figure 2-8. Some days the wind plant generated 5 MW or more. Some days the wind plant output was very low. Hence, this plot illustrates the relatively weak correlation between wind plant output and daily system peak load during the summer peak period. These data support the capacity factor assigned to wind plants by SMUD.

Photovoltaic Plant Performance

Expected hourly PV plant output obtained from PVUSA is presented in Figure 2-9 for single-axis tracking PV designs installed on the SMUD system. This expected hourly PV output is compatible with the 55% capacity factor assigned to single-axis PV plants by SMUD in the 1993 and 1995 *Integrated Resource Plan Update.*

[1] 1993 *Integrated Resource Plan Update*, SMUD, Vol. I and II, October 4, 1993.

[2] 1995 *Integration Resource Plan Update*, SMUD, recent draft.

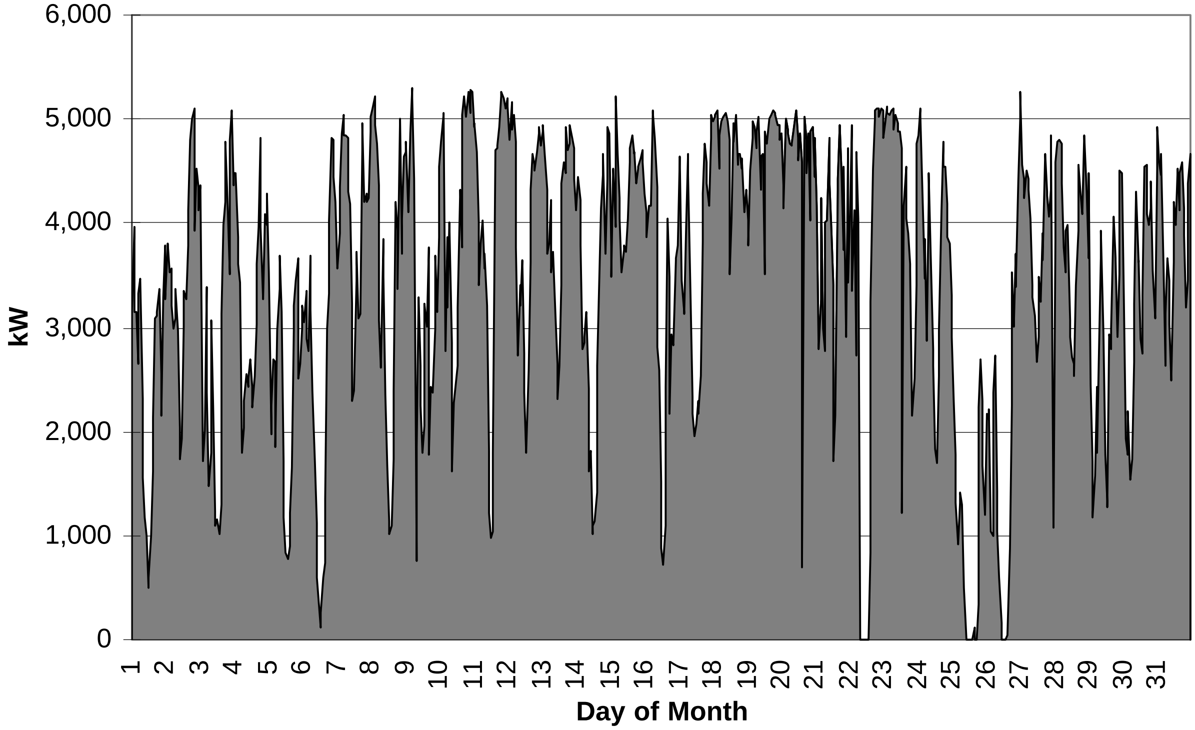

Figure 2-1. Aggregated kW Output of the Solano Wind Plant for July 1994.

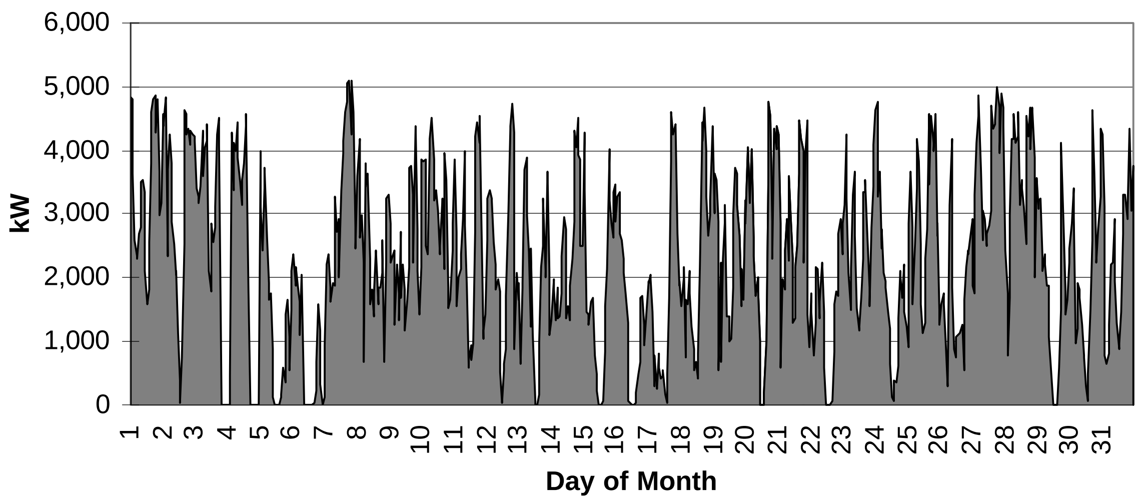

Figure 2-2. Aggregated kW Output of the Solano Wind Plant for August 1994.

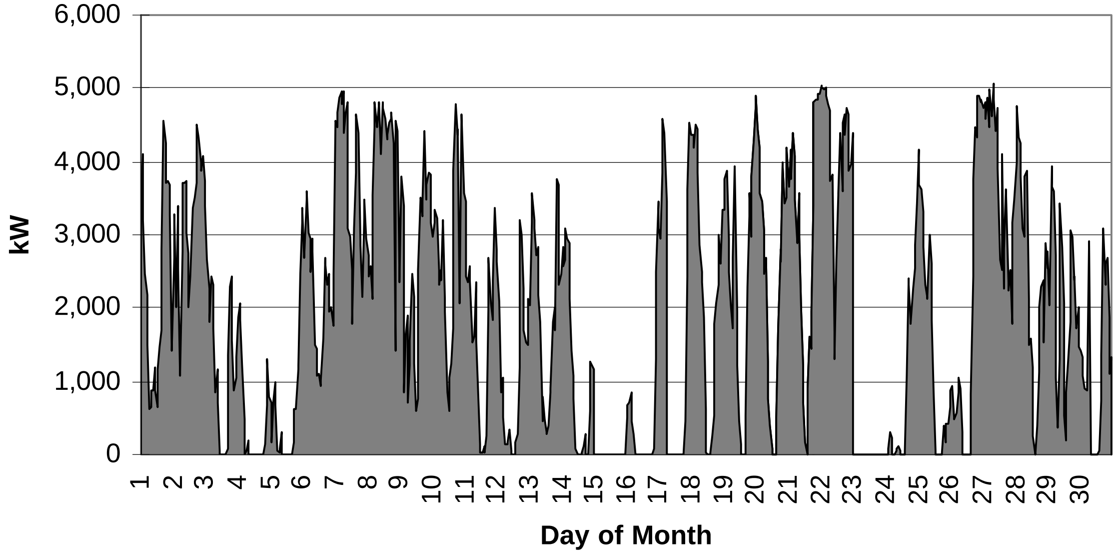

Figure 2-3. Aggregated kW Output of the Solano Wind Plant for September 1994.

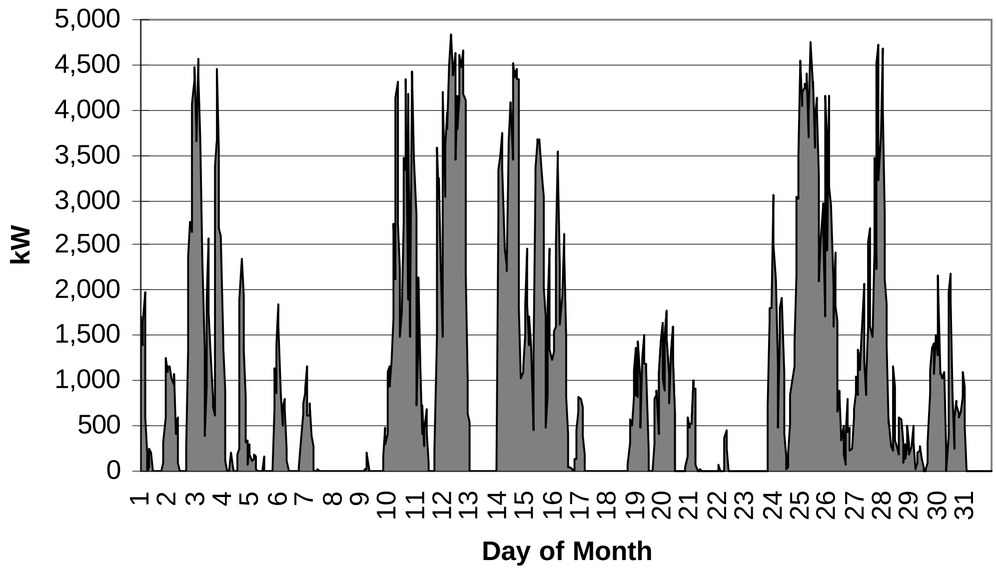

Figure 2-4. Aggregated kW Output of the Solano Wind Plant for October 1994.

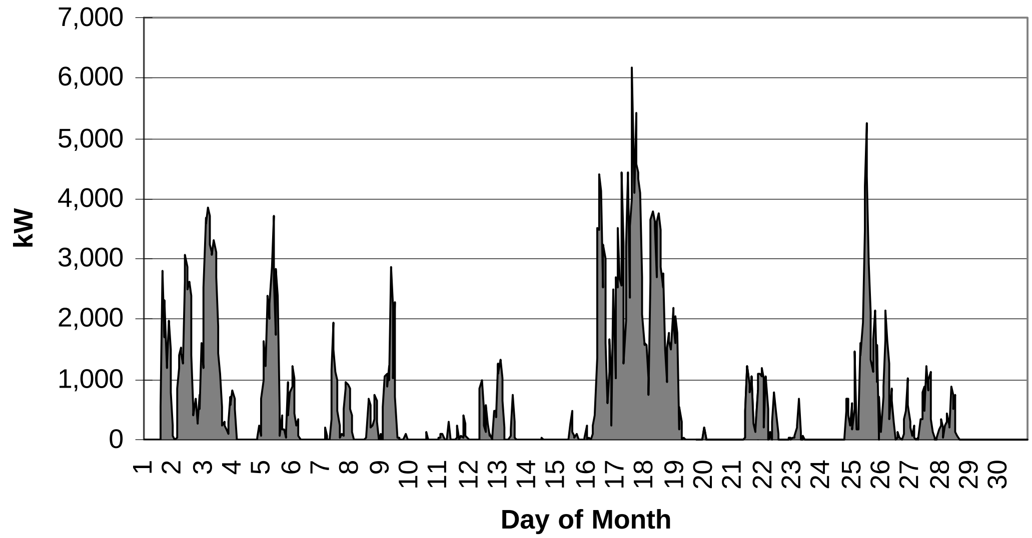

Figure 2-5. Aggregated kW Output of the Solano Wind Plant for November 1994.

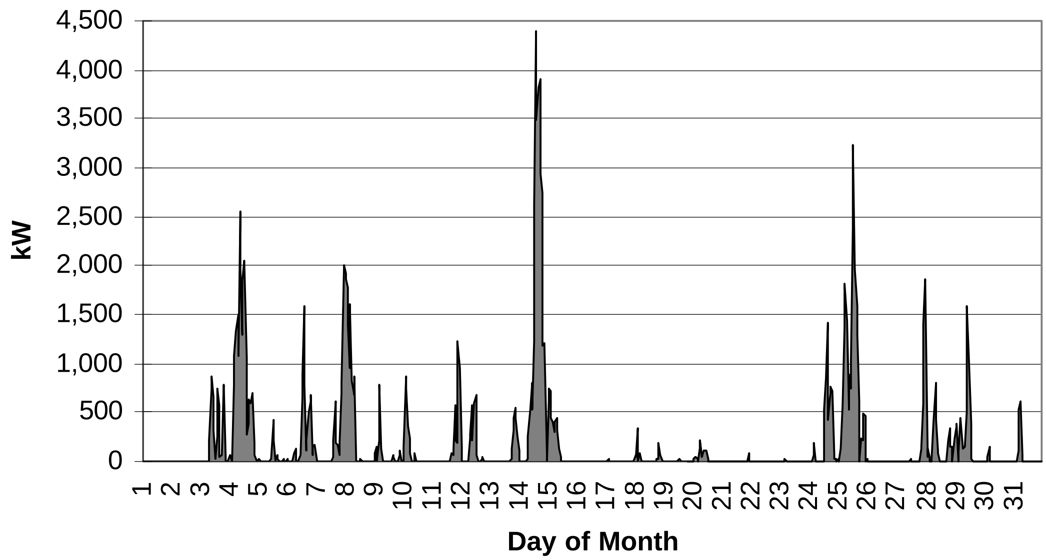

Figure 2-6. Aggregated kW Output of the Solano Wind Plant for December 1994.

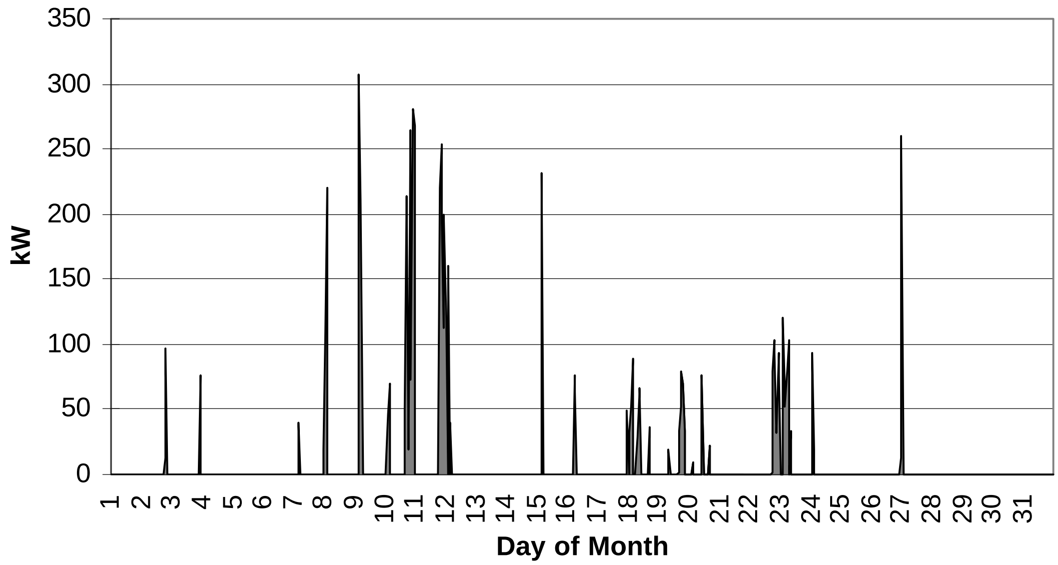

Figure 2-7. Aggregated kW Output Exceeding 5,000 kW for the Solano Wind Plant for July 1994.

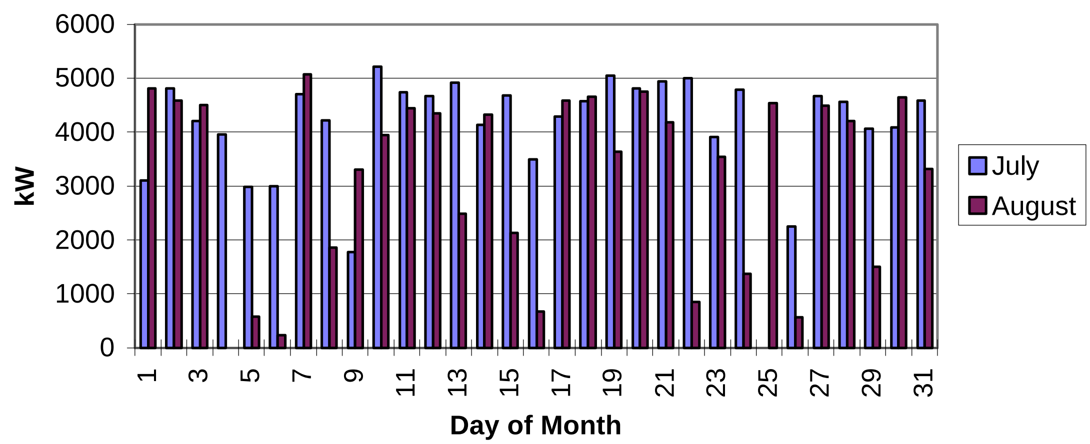

Figure 2-8. Aggregated kW Output of the Solano Wind Plant at 6:00 p.m. for July and August 1994.

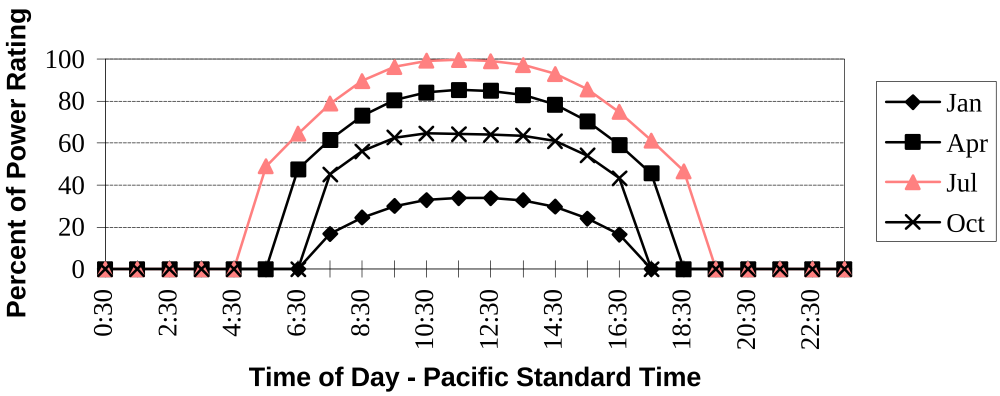

Figure 2-9. SMUD Single-Axis Tracking PV Seasonal Percent of Power Rating.

3. Potential Battery Storage Benefits to Wind and PV Plants

The purpose of this section is to identify potential battery storage benefits to SMUD wind and PV plants, compensating for variations in real-time wind and PV plant output.

Capacity Benefits

Currently the capacity factor assigned to wind plants by SMUD is 15% of nameplate megawatt capacity. The capacity factor assigned to PV plants by SMUD is 55% of nameplate megawatt capacity.[3] The wind and PV performance data presented in Section 2 support these capacity factors.

Adding battery storage to wind and PV plants can make them dispatchable and increase the capacity factors of the renewable resources. In general, to increase solar- and wind-plant capacity factors, the battery storage megawatt and megawatt-hour requirements must be compatible with SMUD generation system reliability criteria and daily system load shape characteristics. In addition, SMUD must have a need for new capacity in the time frame being studied.

The 1993 SMUD *Integrated Resource Plan Update* indicates that both wind and PV resource additions are tentatively planned over the next several years, as shown in Table 3-1.[4]

5 MW of wind turbines are now on line at Solano, and their performance from July 1, 1994, through December 31, 1994, is presented in Section 2 of this report. Conversations with SMUD personnel in 1994 indicated that 45 MW more of wind turbines were tentatively scheduled to be added at Solano in 1996 rather than, as shown in Table 3-1, in 1997. Thus, for this analysis, it was assumed that 50 MW of wind turbines would be operating at Solano in 1996 and that the 50-MW wind-plant capacity factor is 15% of nameplate megawatts, or 7.5 MW (without battery storage). *Note: The additional 45 MW of wind is no longer being planned.*

Table 3-1. Planned SMUD Wind and PV Plant Resource Additions

Year	Nameplate MW	Renewable Resource Description
1994	5	Wind
1995	1	PV
1996	1	PV
1997	45	Wind
1997	1	PV
1998	1	PV
1999	1	PV
2000	50	Wind
2000	1	PV
2001	1	PV
2002	1	PV
2003	1	PV
2004	3	PV
2005	12	PV
2006	12	PV
2007	12	PV
2008	12	PV
2009	12	PV
2010	12	PV
2011	12	PV
2012	12	PV
2013	12	PV
2014	12	PV

Existing SMUD PV resources include 2 MW at Rancho Seco, 200 kW at Hedge, and 100 4-kW residential PV installations at various locations throughout the SMUD service area. In 1994, conversations with SMUD personnel indicated that SMUD planned to add an additional 300 kW of PV at Hedge. For this analysis, it was assumed that 500 kW of PV would be installed at Hedge in 1996 and that the resulting 500-kW Hedge PV plant capacity factor is 55% of nameplate kilowatts, or 275 kW (without battery

[3] Both the 1993 and 1995 *Integrated Resource Plan Update* assign 55% capacity factor to PV.

[4] Table 2, Page 17, 1993 *Integrated Resource Plan Update*, Vol. 1, Final Draft, October 4, 1993.

storage). *Note: As of early 1997, an additional 218 kW of PV was added at Hedge, and over 350 4-kW PV systems have been installed.*

In order to increase the capacity factors of the wind and PV resources, battery plant energy storage capability must be adequate to shave the daily peak load during reasonable “worst case” scenario days, when there are low winds or low solar insolation. For the SMUD system, battery energy storage requirements will increase as renewable resource penetration increases on the system, as more kilowatt-hours are required to shave the daily peak loads. In this study, near-term battery storage penetration levels to increase the capacity factors of 50 MW of wind at Solano and the 500-kW Hedge PV plant are considered. Potential battery penetration levels to firm up these and other potential SMUD wind and PV plant additions over the next few years are expected to total less than 50 MW.

Figure 3-1 shows the daily battery discharge requirements for a 50-MW battery to shave the projected SMUD 112°F peak day residual load.[5] Approximately 50 MWh or 1 hour of storage is required to shave the peak day load shape. Figures 3-2 and 3-3 show the daily battery discharge requirements to shave the monthly July (July 14, 1994) and August (August 16, 1994) peaks with 50 MW of batteries. In July, approximately 75 MWh are required over 2 hours, and in August, approximately 99 MWh are required over 3 hours. (A 50-MW battery can shave approximately 100 MWh over 2 hours or 150 MWh over 3 hours; i.e., discharge capacity = 50 MW × number of hours.)

It may also be necessary for battery storage to shave the residual daily peak loads throughout the year to firm up the wind and PV resources. Figures 3-4 through 3-15 show the requirements for a 50-MW battery to shave monthly SMUD peak loads throughout the year assuming 1992 SMUD monthly load data.[6] For all months except April, the daily battery discharge requirements are less than 100 MWh even though the daily load shapes change significantly throughout the year. For the April peak day, the daily battery storage required to shave the peak 50 MW is approximately 125 MWh delivered over a 3-hour period.

Two hours of battery storage appears adequate to back up the wind and PV resources throughout the year until cumulative battery storage penetration approaches 50 MW. Although the batteries have to be available to operate, they do not necessarily have to be operated on a daily charge/discharge cycle to enhance solar and wind capacities to SMUD. Thus, relatively inexpensive light-duty batteries (cycling less than 50 times per year vs. heavy-duty and more costly batteries cycling daily up to 250 times per year) are adequate to back up the wind and PV resources and enhance their capacity factors.

SMUD performed a marginal cost study[7] that presents projected marginal capacity and energy costs from 1995 through 2014 to be used in evaluating alternative supply- and demand-side resources. The annual marginal generation capacity costs for generation with outages are shown in Figure 3-16. These costs are derived from Schedule 2.01 in the 1994 SMUD *Marginal Cost Study* and are used to determine the annual benefits of battery storage in this analysis. After 2014, annual capacity costs are escalated at the study inflation rate of 3.5%.

Spinning Reserve Benefits

The 1994–1996 *SMUD Resource Operating Plan*[8] describes current SMUD operating reserve requirements, including both spinning- and quick-start-(10-minute) reserve requirements. Currently, SMUD must maintain a minimum continuous spinning-reserve margin of 7% of the system load less firm power purchases within the Pacific Gas & Electric (PG&E) control area. In addition, SMUD must maintain spinning reserves equal to 100% of the non-firm power imports.

Both wind and PV plants are intermittent resources and will therefore require SMUD to maintain a spinning-reserve margin of 7% or more. Conversations with SMUD systems operations personnel indicated that assigning a 7% spinning-reserve requirement for PV and wind resources was compatible with SMUD’s operating reserve policy and a reasonable assumption for this analysis.

[5] 1993 SMUD *Integrated Resource Plan Update*, Vol. II, Page 18.

[6] 1992 *Class Load Study*, SMUD Rate Department, December 1993.

[7] 1994 *Marginal Cost Study*, SMUD Resource Planning and Evaluation, Vol. 1 and II, June 2, 1994.

[8] 1994–1996 *Resource Operating Plan*, SMUD Power Systems Operations, Final Draft, February 1994.

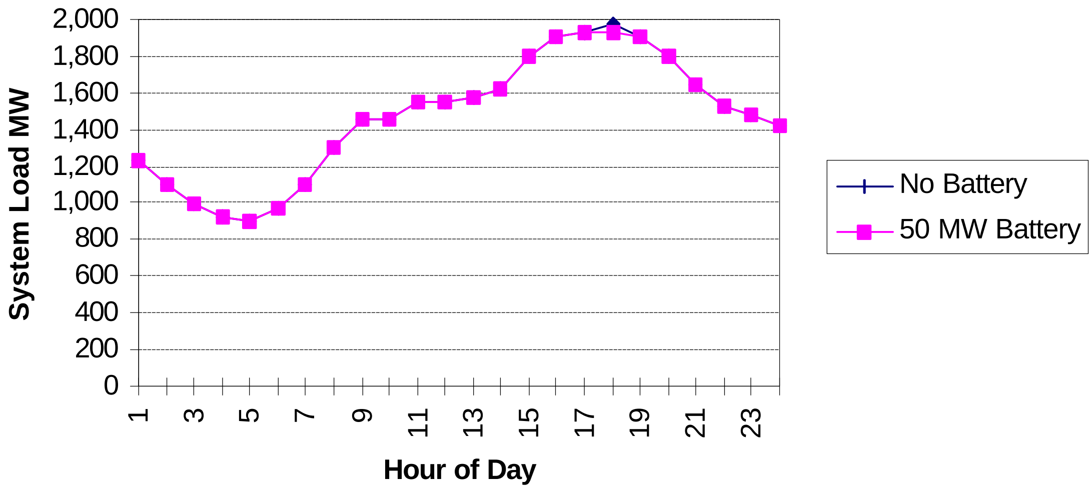

Figure 3-1. Expected Daily Battery Discharge Requirement to Shave Peak—Projected 112°F Peak Day Residual Load.

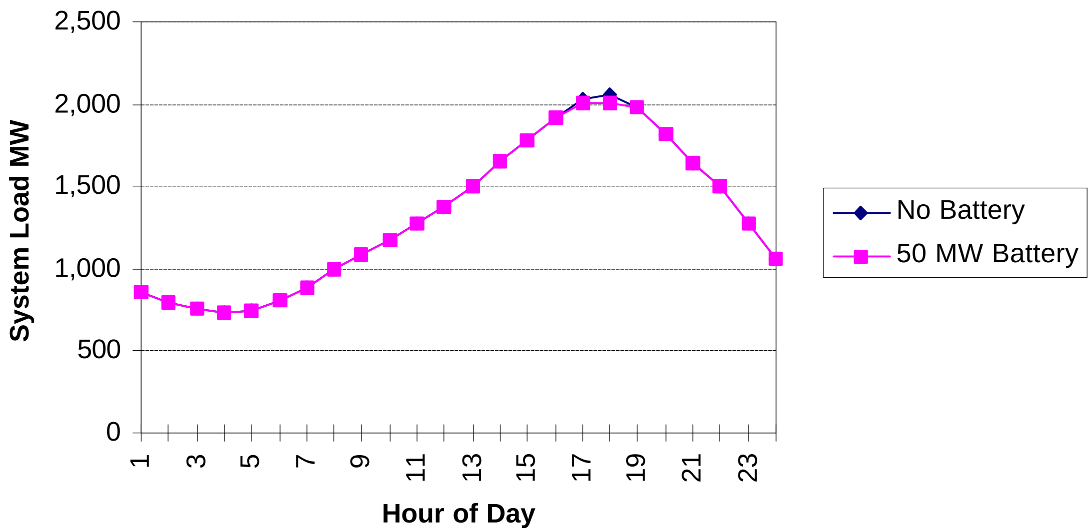

Figure 3-2. Expected Daily Battery Discharge Requirement to Shave Peak—July 14, 1994, Residual Load.

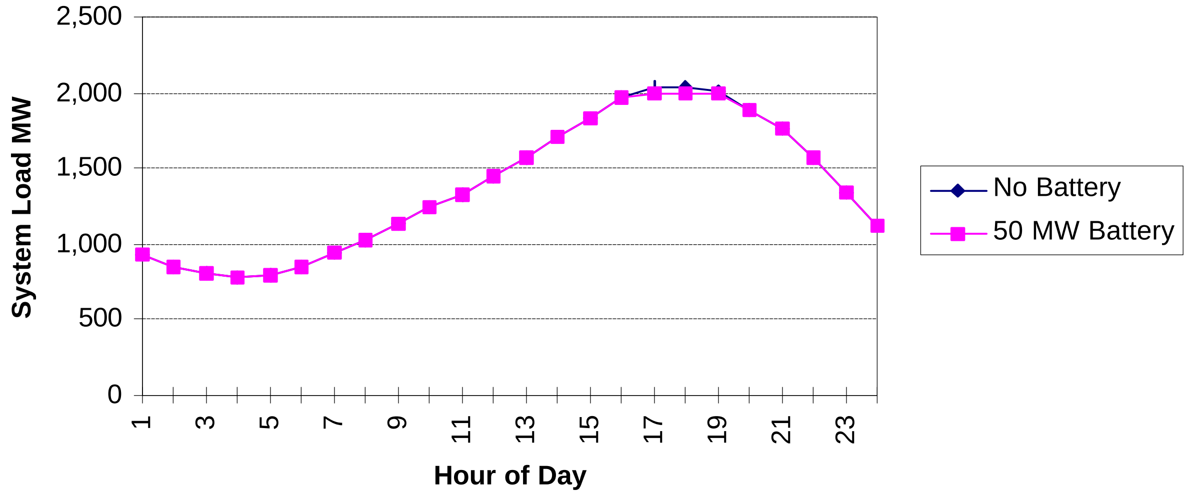

Figure 3-3. Expected Daily Battery Discharge Requirement to Shave Peak—August 16, 1994, Residual Load.

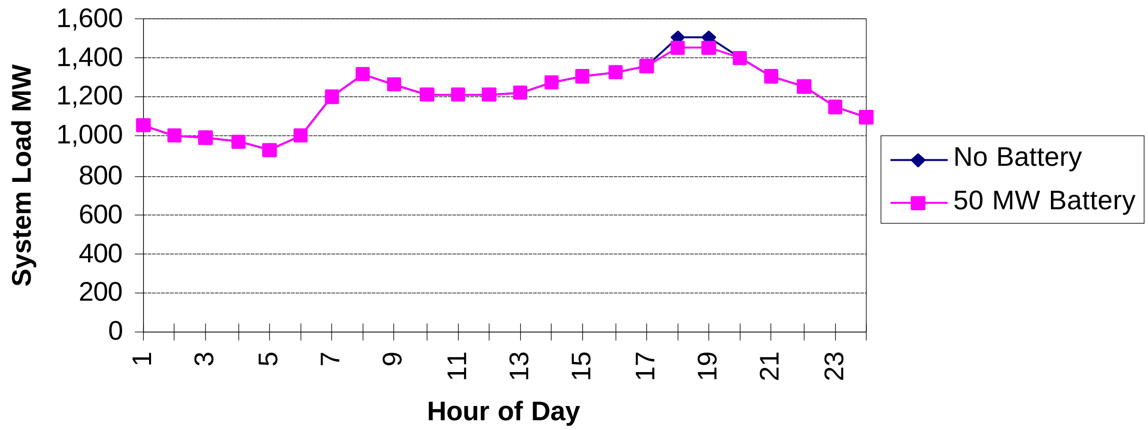

Figure 3-4. Expected Daily Battery Discharge Requirement to Shave Peak—January 1992 Day Load Shape.

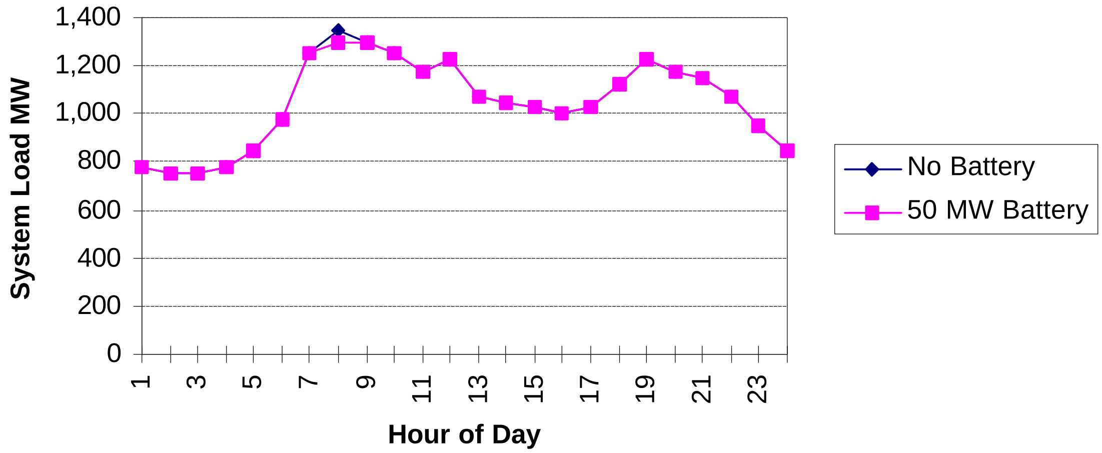

Figure 3-5. Expected Daily Battery Discharge Requirement to Shave Peak—February 1992 Peak Day Load Shape.

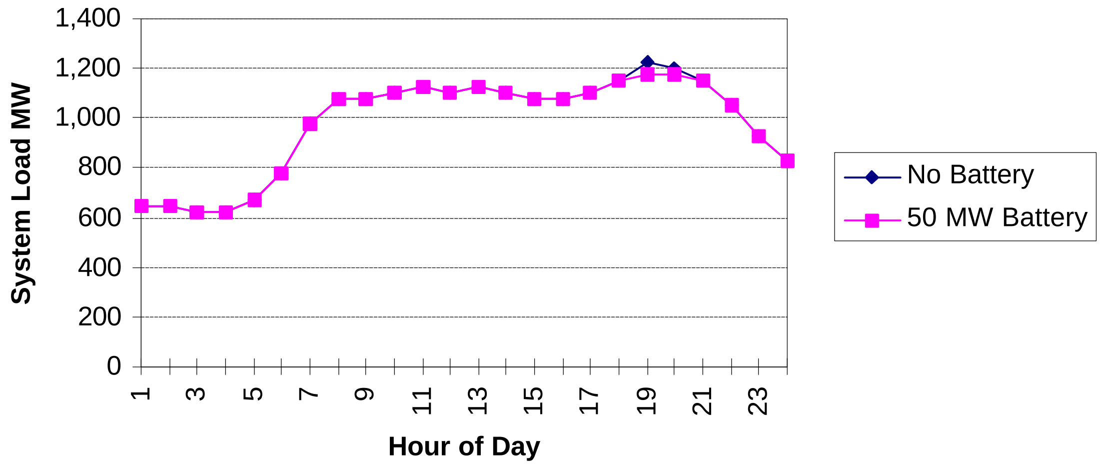

Figure 3-6. Expected Daily Battery Discharge Requirement to Shave Peak—March 1992 Peak Day Load Shape.

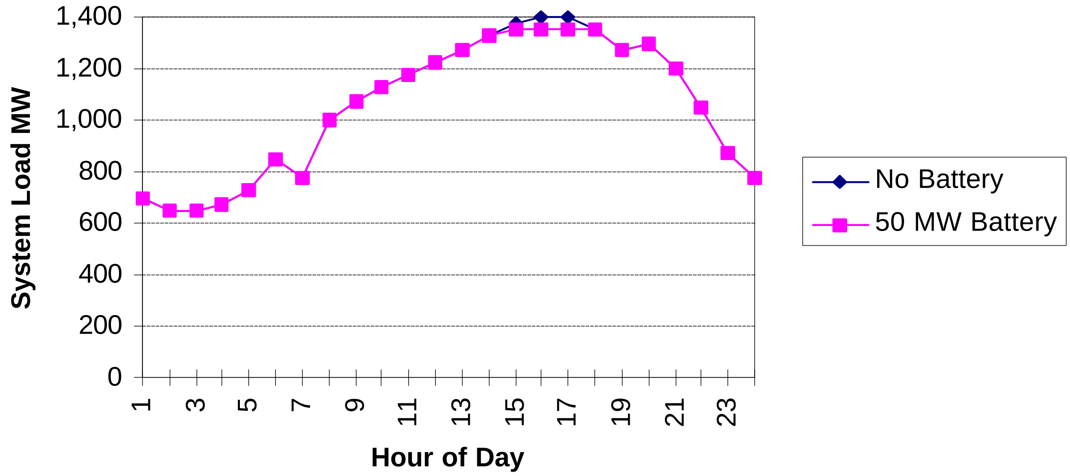

Figure 3-7. Expected Daily Battery Discharge Requirement to Shave Peak—April 1992 Peak Day Load Shape.

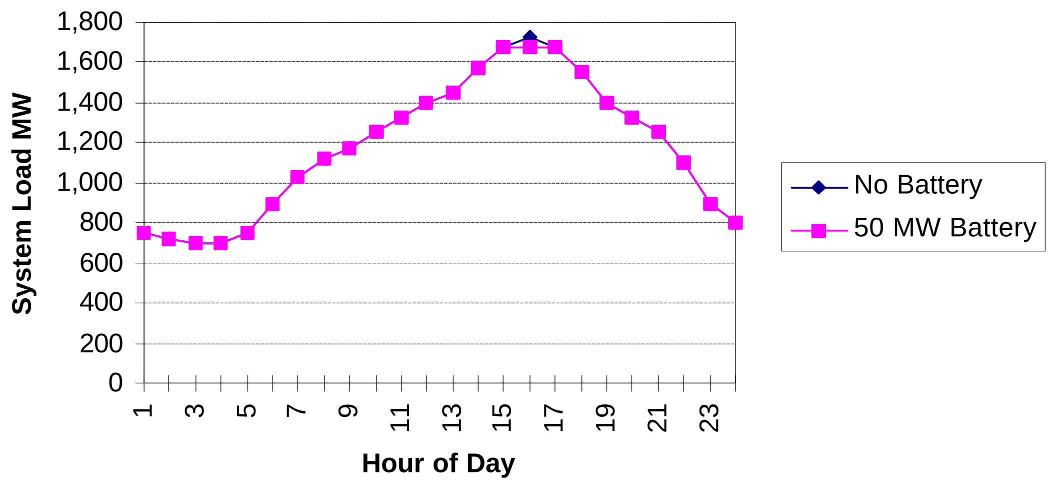

Figure 3-8. Expected Daily Battery Discharge Requirement to Shave Peak—May 1992 Peak Day Load Shape.

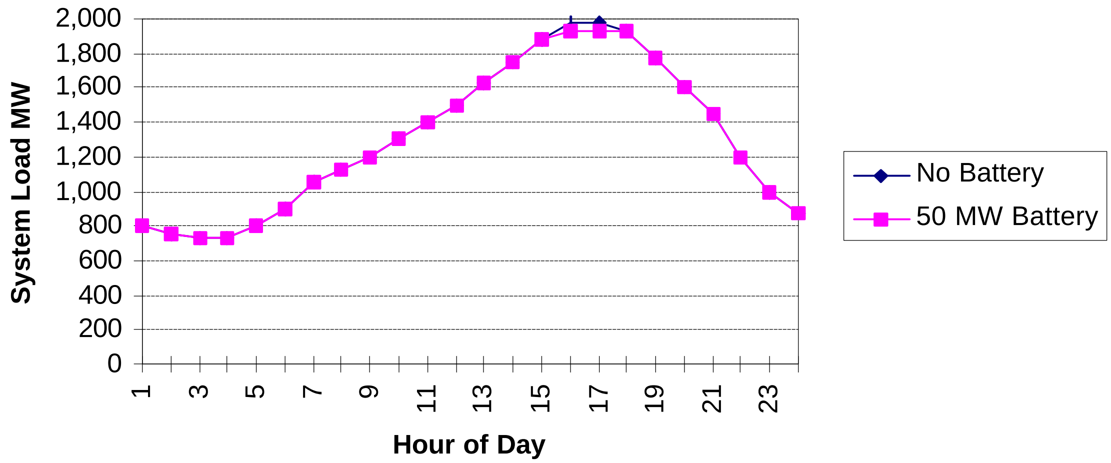

Figure 3-9. Expected Daily Battery Discharge Requirement to Shave Peak—June 1992 Peak Day Load Shape.

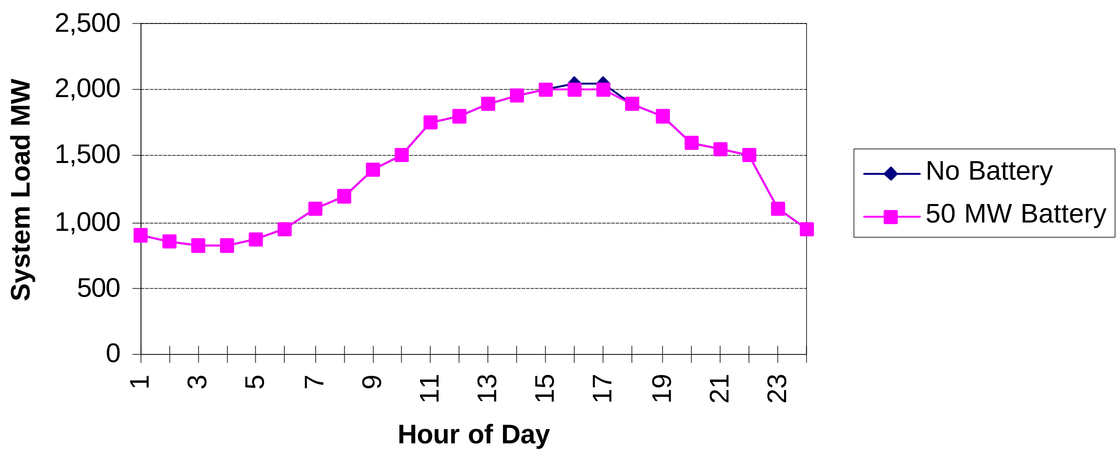

Figure 3-10. Expected Daily Battery Discharge Requirement to Shave Peak—July 1992 Peak Day Load Shape.

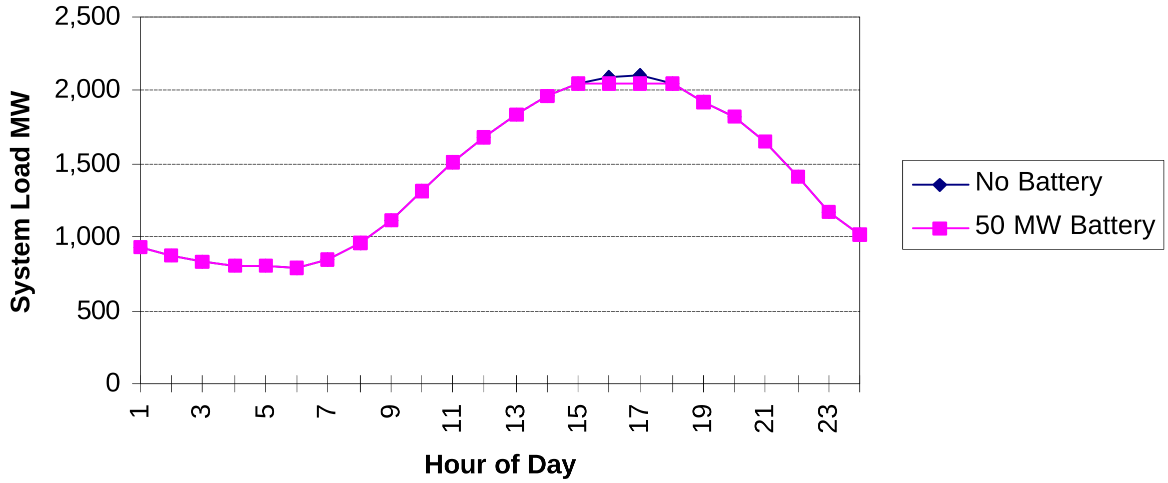

Figure 3-11. Expected Daily Battery Discharge Requirement to Shave Peak—August 1992 Peak Day Load Shape.

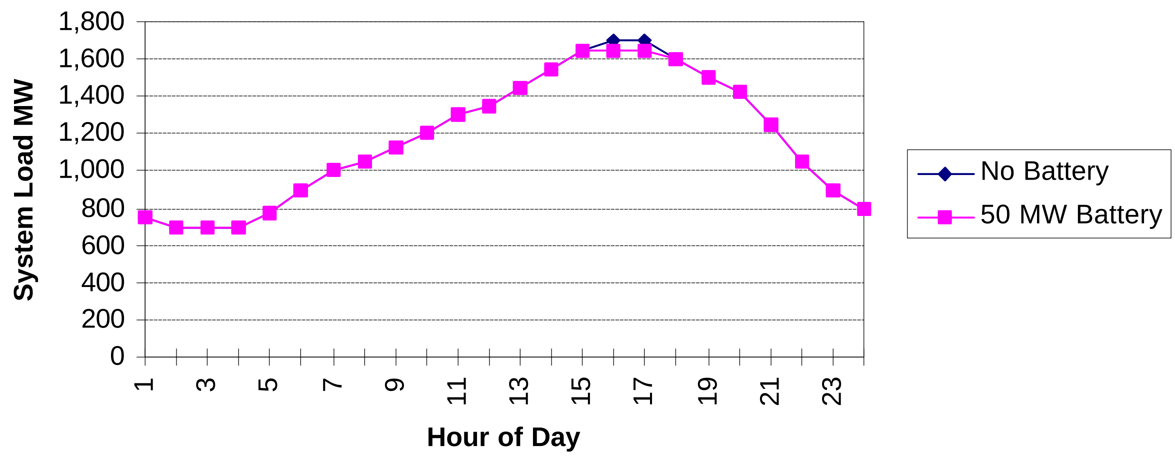

Figure 3-12. Expected Daily Battery Discharge Requirement to Shave Peak—September 1992 Peak Day Load Shape.

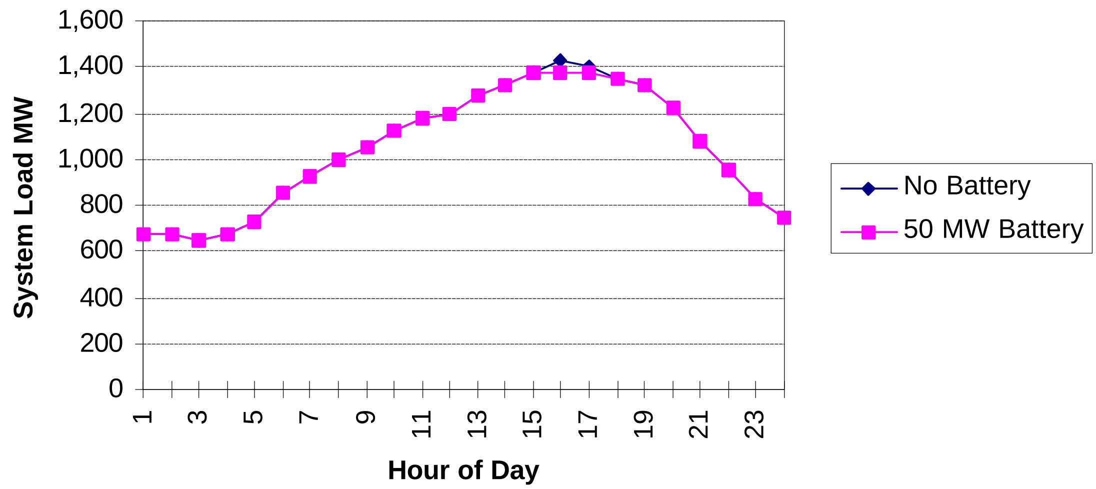

Figure 3-13. Expected Daily Battery Discharge Requirement to Shave Peak—October 1992 Peak Day Load Shape.

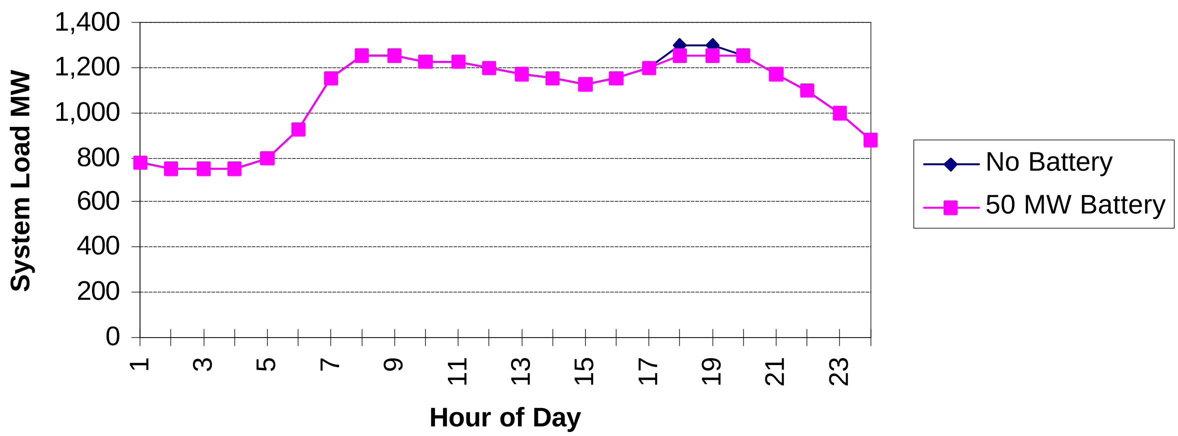

Figure 3-14. Expected Daily Battery Discharge Requirement to Shave Peak—November 1992 Peak Day Load Shape.

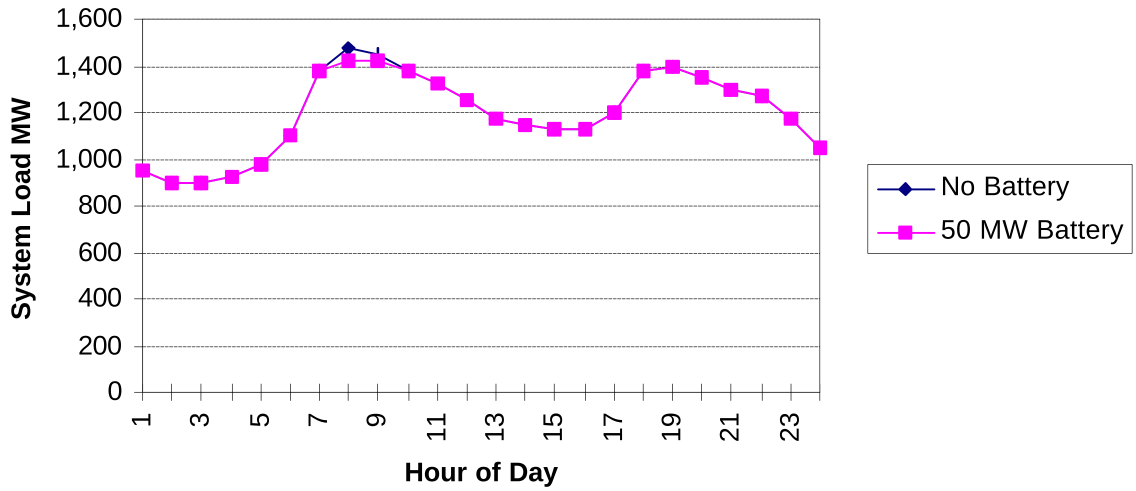

Figure 3-15. Expected Daily Battery Discharge Requirement to Shave Peak—December 1992 Peak Day Load Shape.

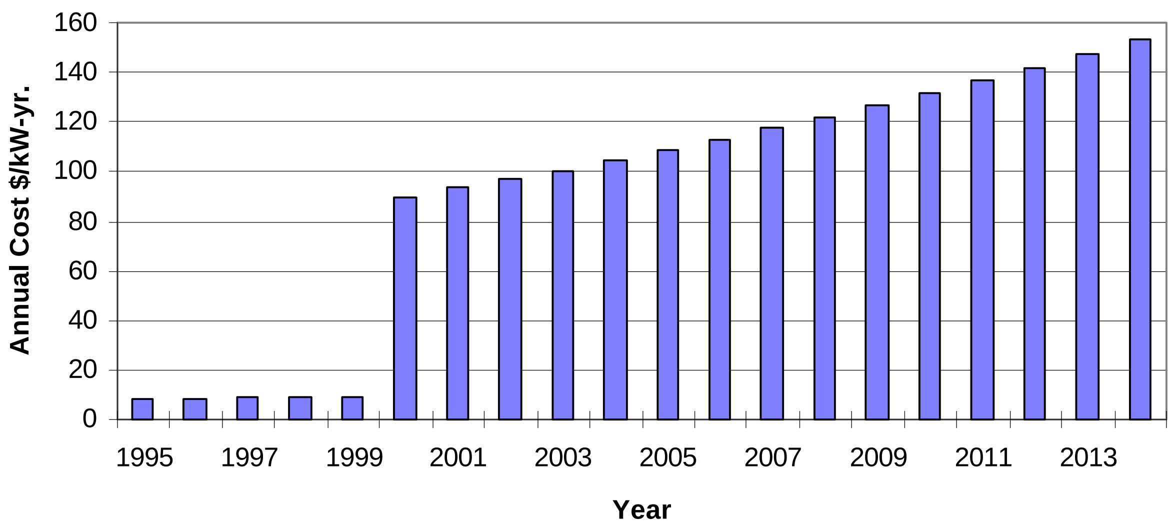

Figure 3-16. Annual SMUD Marginal Capacity Costs.

Battery storage has the capability to be quickly started or changed from charging to discharging in the millisecond time frame. Therefore, battery storage can be added to SMUD wind and PV plants to supply the spinning-reserve requirement for the plants.

Battery storage would be expected to operate infrequently to supply spinning-reserve capability. It is also expected that the batteries would only have to operate until other SMUD generation could be started or replacement power purchased after a sudden generation outage. Thus, battery storage used for spinning reserve would probably not require large megawatt-hour storage capability.

Calculating the potential economic benefits associated with employing battery storage for this application requires determining the expected operating cost penalties resulting from supplying the 7% spinning-reserve requirement without batteries. Spinning reserve typically includes unused megawatt capability of SMUD hydrogeneration and other on-line generation plus purchases from PG&E and others, as described in the 1994-1996 resource operating plan.

For this analysis, it is assumed that incremental increases in spinning-reserve requirements would be supplied by the PG&E Power Service Agreement power purchase, as this is one of the primary sources of SMUD spinning reserve. The PG&E purchase is supplied on a daily basis in 50-MW blocks. In January 1995, the average cost for an unloaded 50-MW block of power was $20.06/MW/day.[9] The minimum load energy requirement is 25% of the 50-MW block.

In 1996, spinning-reserve requirements for 50 MW of wind at Solano would be 3.5 MW, assuming the 7% spinning-reserve margin. The 3.5-MW increase in spinning reserve is expected to require an additional 50-MW block of PG&E spinning reserve about 7% of the time, or 26 days per year, costing about $1,000 per day, or $26,000 per year. There also would be an energy cost penalty during these 26 days, because 12.5 MW of PG&E power during these days is expected to cost significantly more than other available transactions such as economy energy (economy energy is the cheapest electricity available on the spot market). Assuming a $10/MWh penalty, this translates into $3,000 per day, or $78,000 per year. The total annual spinning-reserve penalty for 50 MW of wind at Solano could be as much as $104,000 per year, or $29.74/kW/yr in 1995 dollars.

The $29.74/kW/yr spinning-reserve penalty will also be assumed for the 500-kW PV plants at Hedge.

Transmission and Distribution Benefits

The SMUD 1994 *Marginal Cost Study* presents marginal cost data for transmission, subtransmission, and distribution capacity costs and losses, as well as for generation capacity costs. Schedule 2.11 in the study presents 20 years of demand-related transmission costs from 1995 through 2014. Schedule 2.16 presents 20 years of demand-related subtransmission costs from 1995 through 2014. Schedule 2.20 presents 20 years of demand-related average distribution costs from 1995 through 2014 for the total SMUD system. Schedules 2.21 through 2.30 present area-specific, demand-related distribution costs for the South Natomas, Antelope, Carmichael, Rancho Cordova, Folsom, Pocket, Elk Grove/Laguna, Undeveloped, Galt, and Rancho Murieta areas.

These marginal transmission and distribution (T&D) costs were developed to compare the relative costs of alternative generation resources installed at different voltage levels in the SMUD service area. The costs of resources outside the SMUD service area with specific T&D deferral information are not available. Figure 3-17 presents the projected annual SMUD marginal transmission, and subtransmission, demand-related costs used in this analysis. In this analysis, these transmission and subtransmission cost benefits are applied to battery storage added to the 500-kW PV plant connected to the distribution primary system at Hedge, which is located in the SMUD service area. These T&D benefits are not available to battery storage located at the Solano wind plant because Solano is outside the SMUD service area.

The Hedge PV site is connected to a 12-kV feeder served by the Elk Grove Florin/Gerber 20-MVA 69-kV to 12-kV substation. Because PV is an intermittent source, no T&D capacity benefits are currently available. If dispatchable battery storage is added to the Hedge PV plant, the battery plant must have adequate energy storage to shave the daily substation peak load during local peak-load conditions to attain T&D capacity benefits.

Figure 3-18 shows the daily substation load shape for two days in August 1994 when the temperature exceeded 100°F. Two hours of energy storage appears adequate to shave this local peak for a 225-kW battery storage plant installed at Hedge. In addition, the time of day for this local daily load peak appears to correlate well with the expected total-system daily load during projected annual peak-load conditions, as shown in previous figures. Thus, battery storage located at Hedge would be expected to attain both generation capacity and transmission and subtransmission capacity benefits. Also, transmission and subtransmission facility outage contingencies occur infrequently. Hence, batteries are expected to operate infrequently to back up these transmission and subtransmission facilities, and light-duty batteries are expected to be adequate for this application.

Significant site-specific, distribution capacity benefits may also be obtained for future battery applications that are placed in locations where distribution-substation transformer additions can be deferred. However, no specific transformer addition deferrals could be identified during discussions with SMUD distribution personnel. Distribution capacity benefits may also be attained in addition to transmission and subtransmission capacity benefits for battery storage systems with future residential PV applications in cases where the daily local distribution load shape also correlates with the system native load shape. However, because the distribution system is radial,

[9] Conversation with SMUD Systems Operations personnel.

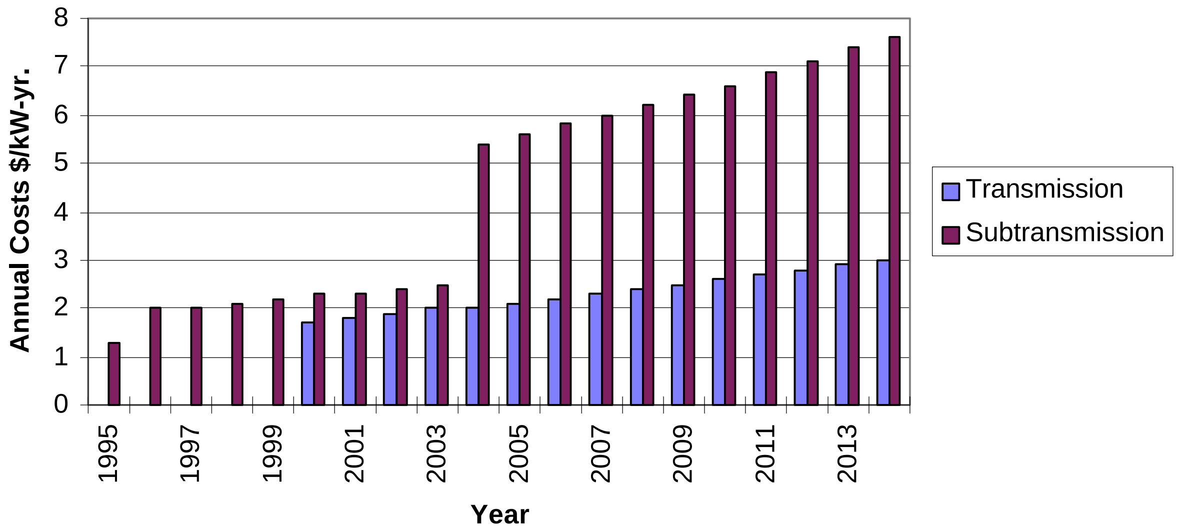

Figure 3-17. Annual Marginal Transmission and Subtransmission Capacity Costs.

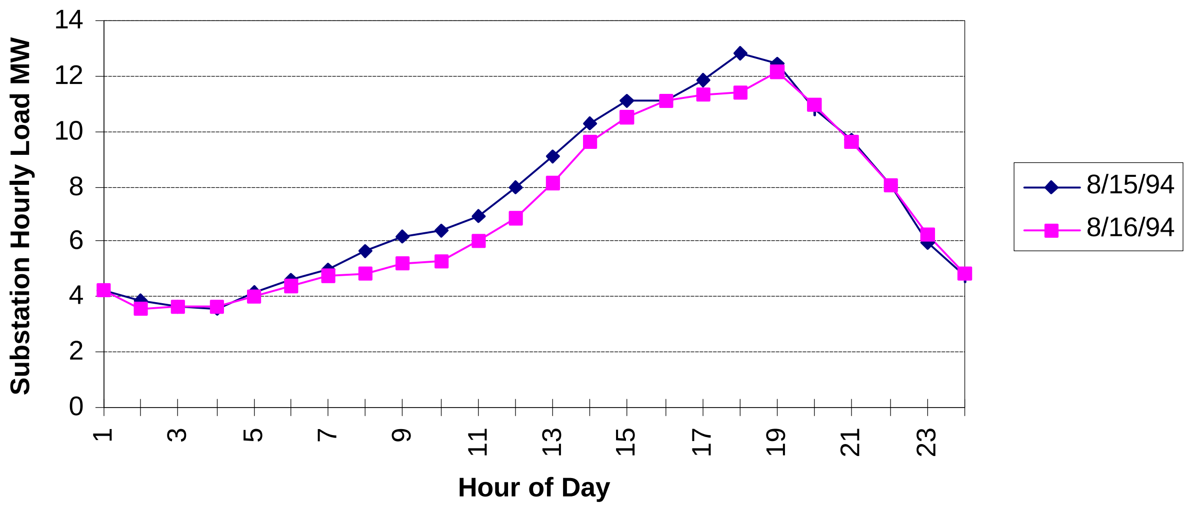

Figure 3-18. Representative Daily Elk Grove Florin/Gerber Substation Load Shape.

batteries must always be discharged to shave the distribution peak to obtain the distribution capacity benefits. Hence, batteries installed in future residential PV applications are expected to be charged and discharged more frequently to attain the distribution capacity benefits.

As stated previously, the above transmission, subtransmission, and distribution-capacity value benefits are not available to battery storage located at the Solano wind plant, which is outside of SMUD's service area. However, adding battery storage to the Solano wind plant may significantly increase Solano wind plant energy production if the full 50 MW of wind turbines are installed at Solano in 1996.

In this case, PG&E will provide 15 MW of reserved (firm) transmission service throughout the year and an additional 35 MW of interruptible transmission service. Conversations with SMUD personnel indicate that the 15 MW of reserved transmission service limit is based on transmission capacity limits in the transmission path from the Solano wind plant to the SMUD service area.

Extrapolating the 5-MW Solano wind plant performance for a good summer wind month represented by July 1994 (shown in Figure 2-1) to 50 MW, almost 60% of the time a 50-MW, wind-plant, hourly megawatt output would exceed 15 MW. In addition, for a small portion of the time, a 50-MW Solano wind-plant hourly output will exceed 50 MW—the combined firm plus interruptible transmission limit. Thus, it is likely that a significant amount of Solano wind plant energy may be lost due to transmission limits, especially during the peak load (and high wind) summer months when the transmission system is heavily loaded.

Battery storage located at the Solano wind plant can be used to store wind energy that would be lost during hours when transmission service is constrained, allowing the energy to be delivered later. In this analysis, the value of potential lost Solano wind plant energy is determined using the summer peak energy costs in Figure 3-19.[10] After 2014, the costs are escalated at the inflation rate. These assumptions are also compatible with current SMUD energy costs obtained from SMUD system operations personnel.

Other Potential Battery Storage Benefits

Two other ways that battery storage can enhance the value of PV and wind plants to SMUD have been identified as described below.

Loss Reduction

Battery storage can reduce losses by PV plants located in SMUD's service area. Batteries can reduce SMUD transmission, subtransmission, and distribution losses by shifting loads from peak periods to off-peak periods during low solar insolation periods, when PV plants are not generating at full output. To provide a significant reduction in annual losses, the batteries must cycle frequently throughout the year. Calculating the benefit requires modeling the expected PV plant output throughout the year, as well as modeling expected variations in system production cost and T&D power flows. Previous experience indicates that the magnitude of these loss reduction benefits can vary widely between specific battery applications and must be evaluated on a case-by-case basis.

[10] *1994 Marginal Cost Study*, Vol. II, Schedule 6.04.

The potential reduction in losses from adding batteries to the Hedge PV plant has not been evaluated in this analysis because the reduction does not appear to be large. First, the PV plants on the SMUD system are already obtaining significant loss-reduction benefits as described in the 1994 *Marginal Cost Study*.[11] Second, the other potential SMUD battery capacity benefits and spinning-reserve applications do not require frequent battery charge/discharge cycling, which tends to result in small loss-reduction benefits.

Regulation Benefits

SMUD's minute-to-minute area regulation requirements are presented in its 1994-1996 *Resource Operating Plan*. SMUD is assessed penalties for area control error (ACE) not crossing zero within 10 minutes more than 12 times per day and for not maintaining a specific ACE-deviation bandwidth.

These regulation requirements and corresponding SMUD-generation regulation assignments are based on expected minute-to-minute system load fluctuations. If the SMUD 50-MW Solano wind plant comes on line, there may be increased minute-to-minute regulation requirements imposed on the rest of the SMUD generation system to accommodate potential minute-to-minute, wind-plant megawatt output fluctuations in addition to minute-to-minute system load fluctuations.

Adding battery storage that can be quickly charged and discharged under control of an automatic generation control system can smooth out wind-plant minute-to-minute output fluctuations. Expected minute-to-minute, Solano wind-plant, output-fluctuation information was not readily available for this analysis, and potential battery storage regulation benefits were not calculated.

[11] 1994 *Marginal Cost Study*, Vol. II, Schedules 4.1 and 4.2, June 2, 1994.

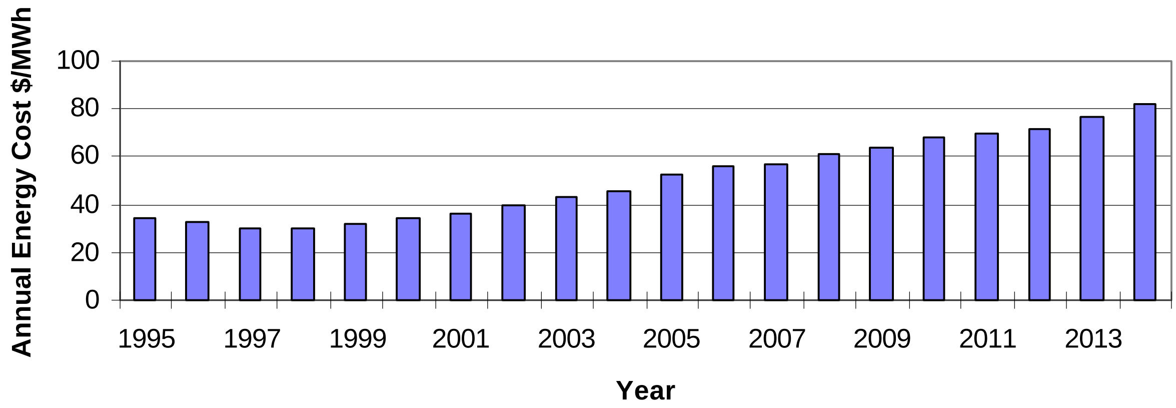

Figure 3-19. Annual SMUD Marginal Energy Costs, Summer Peak Period.

4. Preliminary Benefit-Cost Results

This section presents the preliminary benefit-cost evaluation for battery storage added to two sites—50 MW of wind at Solano and the 500-kW Hedge PV plant.

Economic and Financial Assumptions

The following preliminary benefit-cost assessment is performed in a manner compatible with current SMUD planning practices, using the following general financial parameters[12] obtained from SMUD planning personnel:

- Discount rate equals 5.9%;
- Inflation rate equals 3.5%.

The benefit-cost calculations are performed using a 30-yr present worth of revenue requirement (PWRR) economic analysis. Annual SMUD benefits are determined through 2014 as described in Section 3. After 2014, annual benefits are increased at the 3.5% inflation rate. All annual benefits are then discounted to the beginning of the study period using the 5.9% discount rate.

For these preliminary parametric benefit-cost calculations, battery replacement is assumed every 10 years at a cost of one-third the total battery storage plant capital investment, escalated at the 3.5% inflation rate. Annual battery plant operations and maintenance (O&M) costs are ignored in these preliminary benefit-cost calculations.

Enhancement of Solano Wind Plant Value with Battery Storage

As discussed in Section 3, battery storage can be added to the Solano wind plant site to enhance its capacity value. Assuming a 7.5-MW (15%) capacity of the expected 50-MW Solano wind plant, up to 7.5 MW of battery storage can be added without exceeding the 15-MW firm transmission capability. Review of potential "worst case" battery discharge scenarios indicates that 2 hr of battery storage would be adequate for this application. The first 3.5 MW of battery storage can supply 7% spinning reserve for the wind plant. The next 4 MW of battery storage could provide spinning-reserve benefits for the rest of the system.

In Case 1, a 3.5-MW battery storage plant with 2 hr of storage (7 MWh) is added to the Solano wind plant in 1996. In Case 1a, these batteries increase the wind plant capacity rating 3.5 MW and provide 7% spinning reserve for the intermittent wind resource. In Case 1b, the batteries are also assumed to increase wind plant energy production by delivering 7 MWh of wind plant energy up to 40 times/yr during the summer peak period, energy that is assumed to be lost due to transmission limitations.

Figure 4-1 presents the resulting potential annual benefits of adding a 3.5-MW, 2-hr battery storage plant at the Solano wind plant. Capacity benefits are determined using the SMUD marginal capacity costs presented in Section 3 under "Capacity Benefits." Spinning-reserve benefits are determined using the costs presented in Section 3 under "Spinning Reserve Benefits." The transmission limitation benefits are calculated using the costs presented in Section 3 under "Transmission and Distribution Benefits."

Figure 4-2 presents a parametric analysis of the resulting benefit-to-cost ratio versus battery plant capital investments in 1996 dollars for Case 1—adding a 3.5-MW, 2-hr battery at Solano. In Case 1a, which includes capacity value and spinning-reserve benefits, the break-even battery-plant capital investment is about $1,250/kW. In Case 1b, when transmission limits are also considered, the break-even battery-plant capital investment increases to about $1,300/kW. These benefit-cost results are expected to apply to megawatt-scale battery storage plants of up to 7.5 MW capacity with 2 hr of storage located at Solano.

The potential Solano wind-plant battery storage application is expected to require about 20 to 60 battery charge/discharge cycles a year. Hence, less expensive light-duty batteries are expected to be adequate for a potential megawatt-scale battery storage plant.

[12] *1994-2014 Economic Outlook Update: Demographics, Economic Factors, Cost and Fuel Escalation*, SMUD Resource Planning and Evaluation Department, December 1993.

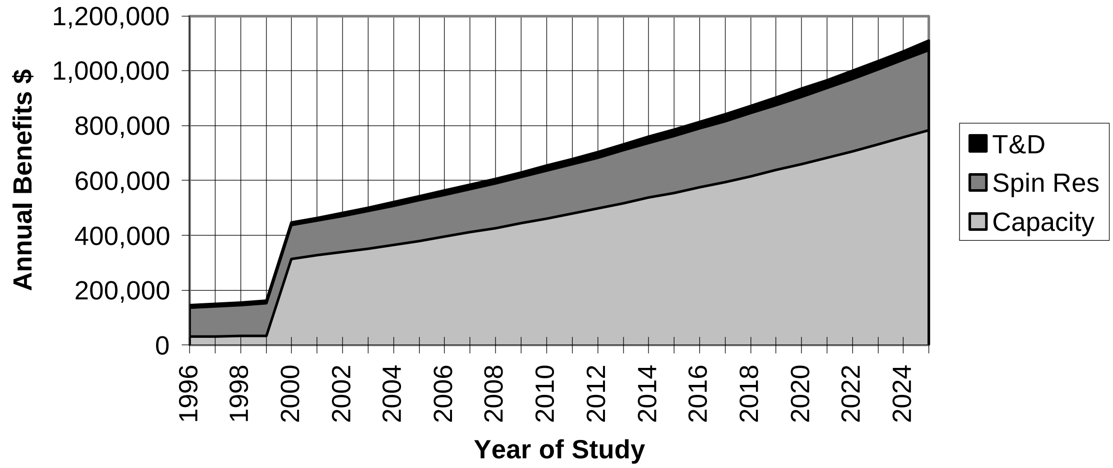

Figure 4-1. Potential Benefits of Adding a 3.5-MW/2-Hr Battery at Solano (Case 1).

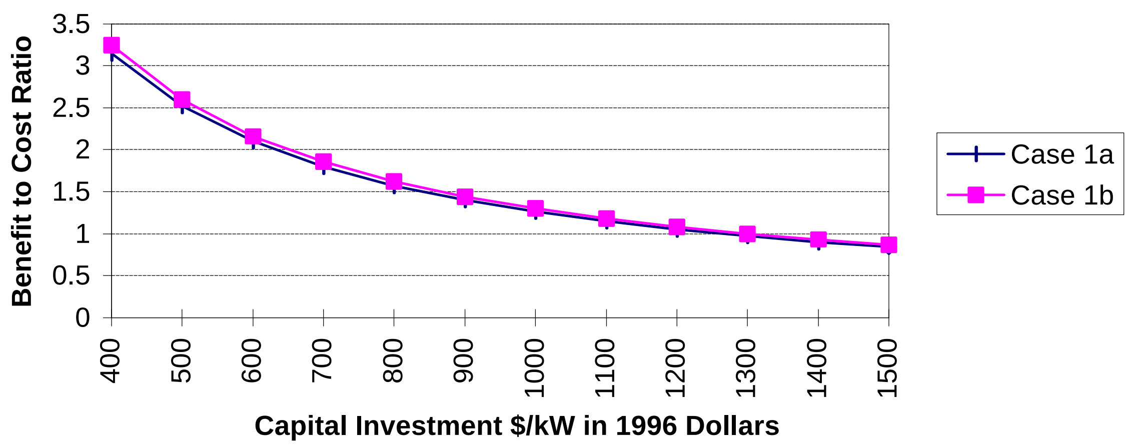

Figure 4-2. Case 1 Break-Even Battery Capital Investment.

Enhancement of Hedge Photovoltaic Plant Value With Battery Storage

As discussed in Section 3, battery storage can be added to the Hedge PV site to enhance the capacity value of the PV plant. Assuming the 275-kW (55%) capacity for the planned 500-kW Hedge PV plant, adding 225 kW of battery storage capacity with 2 hr of storage would be adequate to increase the Hedge PV plant capacity to the full 500-kW capacity. The 225-kW battery storage plant can supply spinning-reserve benefits for the Hedge PV plant as well as the rest of the system and can obtain transmission and subtransmission benefits.

In Case 2, a 225-kW battery plant with 2 hr of storage is added to the 500-kW Hedge PV plant in 1996. The battery plant increases the Hedge PV plant capacity to 500 kW and supplies 225 kW of spinning reserve. Because the battery plant is located in the SMUD service area, transmission and subtransmission capacity benefits of the Hedge PV plant are increased 225 kW.

Figure 4-3 presents the potential annual benefits of adding a 225-kW/2-hr battery storage plant at the Hedge PV site. Capacity, spinning-reserve, and transmission and subtransmission capacity benefits are determined using the SMUD marginal cost data presented in Section 3.

Figure 4-4 presents a parametric analysis of resulting benefit to cost ratio versus battery plant capital investment in 1996 dollars for Case 2—adding a 225-kW battery plant at Hedge. In Case 2, the break-even battery capital investment is about $1,300/kW.

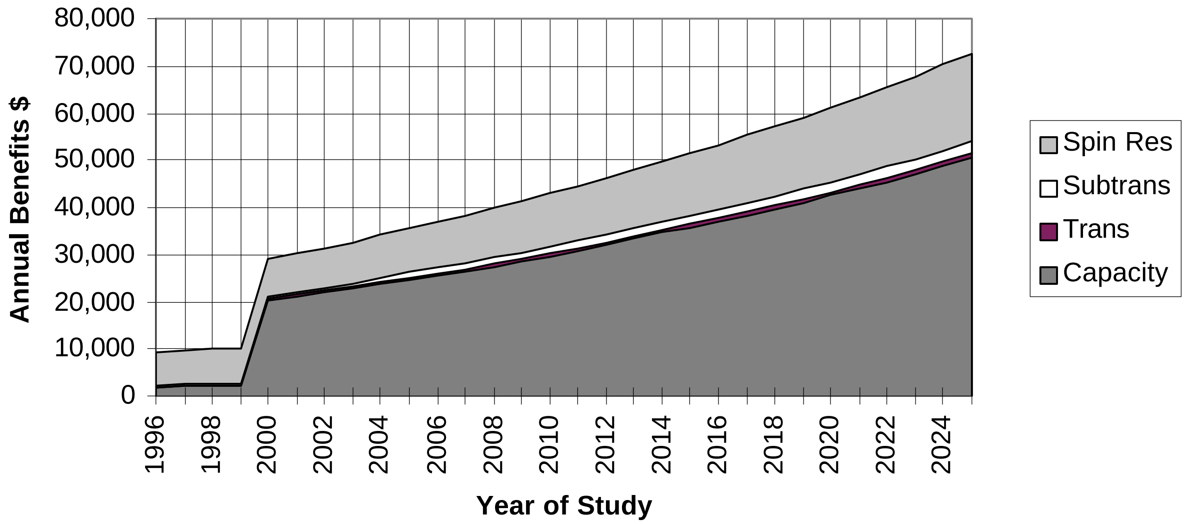

Figure 4-3. Potential Benefits of Adding a 225-kV/2-Hr Battery at Hedge (Case 2).

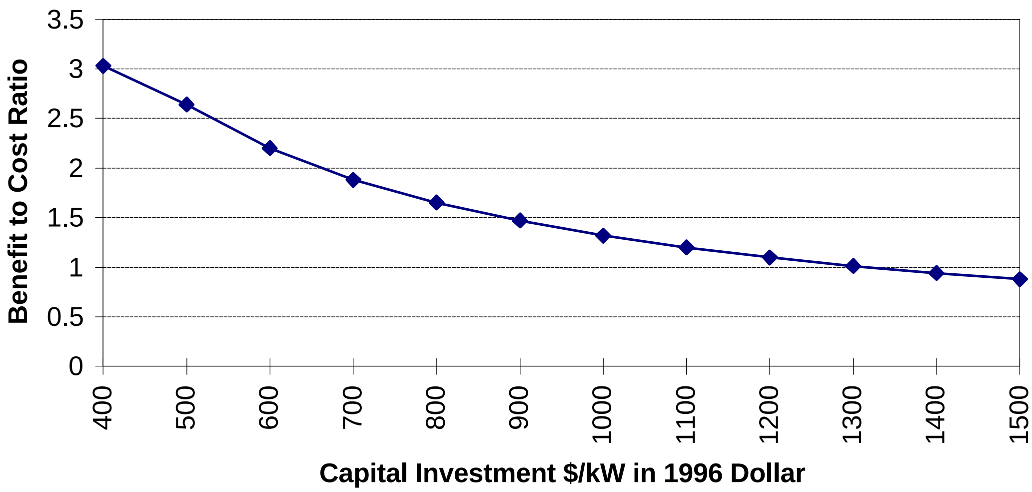

Figure 4-4. Case 2 Break-Even Battery Capital Investment.

The potential Case 2 Hedge PV-plant battery storage application is expected to require less than 50 battery charge/discharge cycles a year to obtain the above benefits. Hence, less expensive light-duty batteries are expected to be adequate for this Hedge PV plant application.

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5. Conclusions and Recommendations

Conclusions

Below are some conclusions and observations:

- The results of this analysis indicate that battery storage can significantly enhance the economic and operational value of the Solano wind plant and the Hedge PV plant.

- The preliminary benefit-cost calculations indicate that the break-even capital investment for battery storage installed to enhance the value of the expected 50-MW Solano wind plant ranges from about $1,250/kW to $1,300/kW. This applies to megawatt-scale battery storage plants of up to 7.5 MW capacity with 2 hr of storage located at the Solano wind plant site.

- The preliminary benefit-cost calculations indicate that the break-even capital investment for battery storage installed to enhance the benefits of the 500-kW Hedge PV plant is about $1,300/kW. This applies to battery storage plants up to 225 kW with 2 hr of storage located at the Hedge PV plant site.

- Approximately 20 to 60 battery charge/discharge cycles a year are required for both the Solano wind plant and Hedge PV plant applications. Thus, less expensive light-duty batteries will be adequate.

- The break-even battery storage capital investments determined during this analysis preliminary evaluation for both Solano and Hedge applications are comparable with battery storage plant cost estimates.

Recommendations

- It is recommended that SMUD obtain cost estimates from vendors for a 1-to-4-MW battery storage plant with 2 hr of storage for possible use with the Solano wind plant. Cost estimates for Solano should include both light-duty and heavy-duty batteries, as plans are to investigate potential regulation benefits.

- It is recommended that SMUD obtain cost estimates from vendors for a 200-to-250-kW battery storage plant with 2 hr of storage for possible use with the Hedge PV plant. Cost estimates for Hedge should include only light-duty batteries.

- It is recommended that the cost estimates to be obtained from battery storage vendors contain both purchase and leasing options.

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