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Innovative Applications of Energy Storage in a Restructured Electricity Marketplace Phase III Final Report

Joe Iannucci, Jim Eyer, and Bill Erdman

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

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Innovative Applications of Energy Storage In a Restructured Electricity Marketplace Phase III Final Report

A Study for the DOE Energy Storage Systems Program

Joe Iannucci, Jim Eyer, and Bill Erdman
Distributed Utility Associates
1062 Concannon Blvd.
Livermore, CA 94550

Abstract

This report describes Phase III of a project entitled *Innovative Applications of Energy Storage in a Restructured Electricity Marketplace*. For this study, the authors assumed that it is feasible to operate an energy storage plant simultaneously for two primary applications: 1) energy arbitrage, i.e., buy-low-sell-high, and 2) to reduce peak loads in utility "hot spots" such that the utility can defer their need to upgrade transmission and distribution (T&D) equipment. The benefits from the arbitrage plus T&D deferral applications were estimated for five cases based on the specific requirements of two large utilities operating in the Eastern U.S. A number of parameters were estimated for the storage plant ratings required to serve the combined application: power output (capacity) and energy discharge duration (energy storage). In addition to estimating the various financial expenditures and the value of electricity that could be realized in the marketplace, technical characteristics required for grid-connected distributed energy storage used for capacity deferral were also explored.

Acknowledgement

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Acronyms

C&I	commercial and industrial
CHP	Combined Heat and Power
DRs	distributed resources
DS	distributed energy storage
DOE	Department Of Energy
DOBs	dynamic operating benefits
DRs	distributed resources
DSO	Distribution System Operator
DUA	Distributed Utility Associates
ESCOs	energy service companies
ESPs	Energy Service Providers
ESS	Energy Storage Systems
FERC	Federal Energy Regulatory Commission
IEEE	Institute of Electrical and Electronic Engineers
I/C	interruptible or curtailable (tariffs)
I^2R	current squared times resistance (equals power)
LLC	Limited Liability Company
LMPs	locational marginal prices
NPV	net present value
O&M	operating and maintenance
PBR	performance-based rates or rate-making
PJM	Pennsylvania, New Jersey, Maryland
PQ	power quality
PW	present worth
SMOs	Storage Market Opportunity
RTOs	regional transmission operators
T&D	transmission and distribution
THD	total harmonic distortion
TSO	Transmission System Operator
UPS	uninterruptible power supply
VAR	volt amp reactive

Executive Summary

Goal and Scope

This project is a continuation of a study initiated in 1998 that defined several possible electricity-provider scenarios that could use energy storage after the restructuring of the U.S. electric utility industry. For this Phase III study, the authors worked under the assumption that it is feasible to operate an energy storage plant simultaneously for two primary applications: 1) energy arbitrage, and 2) to reduce peak load on a utility grid, which would enable the utility to defer the need to upgrade transmission and distribution (T&D) equipment. Possible secondary applications were considered and related storage system benefits are described in Appendix A – Secondary Benefits. The economics of energy storage were evaluated for the combined application involving arbitrage (buy-low-sell-high benefits) plus T&D deferral as the primary benefits.

The benefits from the arbitrage plus T&D deferral applications were estimated for five cases based on the specific requirements of two large utilities operating in the Eastern U.S. A number of parameters were estimated for the storage plant ratings required to serve the combined application: power output (capacity) and energy discharge duration (energy storage). In addition to estimating the various financial expenditures and the value of electricity that could be realized in the marketplace, technical characteristics required for grid-connected distributed energy storage (DS) used for capacity deferral were also explored.

The authors solicited vendors' perspectives for this Phase III effort to: 1) ensure the technical requirements for the combined applications were feasible, and 2) verify that the business assumptions were sound. A consequence of this activity was to help validate the value proposition of the compatibility of these two applications. These activities also provided an opportunity to engage key stakeholders in a dialogue about real and perceived market challenges as well as providing a quantification of the costs and benefits of DS for this important industry sector.

Based on the vendor information and financial analysis, the market opportunity was clarified and included the evaluation of market challenges and market development needs and opportunities. To address the risk/reward structure gap, it is believed that there will need to be certain warranties and guarantees in place before utilities will widely adopt the use of storage for T&D deferral. To address these immediate barriers, many of the suggestions for future work revolve around creating familiarity with storage devices through demonstration projects. This increased familiarity can serve as the basis of a detailed plan for encouraging development of this market.

Conclusions from this effort identified a significant potential to deploy DS thus providing important benefits associated with both arbitrage transactions and utility T&D capacity upgrade deferral. Results from analysis of the Pennsylvania, New Jersey, and Maryland (PJM) region in the central U.S. East Coast indicated that arbitrage benefits for ten years of operation are on the order of \$300/kW. Single year T&D capacity upgrade deferrals are worth as much as $1,000/kW of storage installed. These benefits appear to be additive and even more benefits can be earned by portable storage systems. Locations with suitable conditions for these applications may amount to tens of gigawatts.

1. Introduction

1.1. Purpose

The purpose of this study, which is the third phase of an ongoing assessment, was to evaluate the merits of using grid-connected distributed energy storage (DS) for high value utility applications. Specifically, DS was analyzed for two primary applications:
1) energy buy-low-sell-high transactions (energy arbitrage, or arbitrage), and
2) transmission and distribution upgrade deferral (T&D deferral). The analysis was performed assuming that a single DS plant could satisfy both applications.

1.2. Background

Phase I

Phase I of this study involved broad characterizations of a wide range of innovative ways that storage could be used in the electric supply system of the future, including customer-sited storage.[1] It addressed ways to expand the envelope of possible storage applications and suggested creative uses for storage. It also presented many possibilities for communicating the value and flexibility of storage.

Nine "stretch scenarios" were developed that included use of storage in a restructured electricity industry. They represented innovative and potentially significant uses of electric energy storage, without regard to financial or institutional hurdles.

The common themes determined from this assessment of these scenarios are as follows:

- storage is more likely to be installed at customer sites than coupled to central power plants.
- expanded use of storage is consistent with cleaner energy systems.
- packaging, ease of use, low initial cost, and high reliability (rather than efficiency and energy density) are the key technology factors in several major market opportunities.
- regulatory structures that allow more freedom to solve problems with innovative approaches would be more likely to lead to increased uses of storage.

Based on their potential to significantly impact the overall energy marketplace, the five most compelling of the stretch scenarios were identified. From those scenarios, five specific "Storage Market Opportunities" (SMOs) were defined in broad terms. The primary outcome for this Phase of the project was to document an auditable process, which was used to select the most promising of the five SMOs for a more in-depth evaluation.

Phase II

Phase II of this project was a detailed evaluation of the five most promising SMOs from Phase I. The authors concluded that a significantly valuable combination of benefits (energy, capacity, and power quality/reliability enhancement) was achievable if electric utilities used energy storage systems for high value T&D applications in regions with high power cost volatility. Based on a rough-cut economic and market evaluation, energy storage appeared to be very competitive for providing up to 24 GW/120 GWh during the years 2001-2010. Such storage would be worth $218/kWh installed ($2001), for a total of $26 billion in gross economic benefits in the U.S.[2]

1.3. Phase III Scope

For this study (Phase III), it was assumed that it is feasible to operate an energy storage plant simultaneously for two primary applications developed in the earlier phases of the study: 1) energy arbitrage, and 2) to reduce peak load on utility "hot spots" such that the utility can defer the need to upgrade T&D equipment. Possible secondary applications were considered and related storage system benefits are described in Appendix A – Secondary Benefits. It was determined that these secondary benefits, while large, were not compatible with the primary benefits and hence they were not included in the final economic evaluation. Therefore, for the study, storage was evaluated for the combined application involving arbitrage plus T&D deferral.

The benefits from the arbitrage plus T&D deferral applications were estimated for five cases (Cases 1a-d and Case 2) based on the specific requirements of two large utilities operating in the Eastern U.S. A number of parameters were estimated for the storage plant ratings required to serve the combined application: power output (capacity) and energy discharge duration (energy storage). In addition to estimating the various financial expenditures and the value of electricity that could be realized in the marketplace, technical characteristics required for grid-connected DS used for capacity deferral were also explored.

Vendors' perspectives were sought for this Phase III effort. The reason was to make sure the technical requirements for the combined applications were feasible and that the business assumptions were sound.

Based on the vendor information and financial analysis, the market opportunity was clarified and included an evaluation of market challenges and market development needs. This can serve as the basis of a detailed plan for encouraging development of this market.

1.4. Phase III Summary of Results

Significant potential exists to deploy distributed energy storage such that the same plant can provide significant benefits associated with both energy buy-low-sell-high transactions (energy arbitrage) and utility T&D capacity upgrade deferral. Results from an analysis of the Pennsylvania, New Jersey, and Maryland (PJM) region in the central U. S. East Coast indicated that arbitrage benefits for ten years of operation are on the order of $300/kW. Single year T&D capacity upgrade deferrals are worth as much as $1,000/kW of storage installed. These benefits appear additive and even more benefits can be earned by portable storage systems. Locations with suitable conditions for these applications may amount to tens of gigawatts.

Section 2. Storage Benefits and Discharge Duration

2.1. High Value Utility Applications for Distributed Storage

This section describes the methodology used to estimate financial benefits from grid-connected, distributed energy storage plants for two primary applications: 1) energy arbitrage, and 2) transmission and distribution upgrade deferral (T&D deferral).

Some possible supplemental benefits considered for this study are described in Appendix A. Note that the only benefits considered are those that can be directly monetized. Other possible less tangible benefits, such as enabling renewables or increased grid security were not considered.

This section also describes how storage plant power output rating and discharge duration are determined.

2.2. Storage Benefits Estimation Methodology

The following sections describe the data and the methodology used to estimate the benefits (arbitrage and T&D deferral) associated with energy storage use.

Energy Buy-Low-Sell-High (Arbitrage) Benefit

Arbitrage involves purchase of inexpensive electricity available during periods when demand for electricity is low to charge the storage plant, so that the low priced energy can be used or sold at a later time when the price for electricity is high. (Note, in this context "sales" are mostly or entirely to the utility's end-users, though in more general terms sales could be made via a deregulated wholesale/commodity electricity marketplace.)

To estimate the arbitrage benefit, a simple storage dispatch algorithm was used. It has the logic needed to determine when to charge and when to discharge storage to optimize the financial benefit. Specifically, it determines when to buy and when to sell electric energy based on price.

Three data items were used in conjunction with the dispatch algorithm. They are:

1. historical chronological price data for one year (8,760 hours)
2. energy storage round trip efficiency
3. the number of hours that storage can discharge at full output rating (storage duration)

The simple dispatch model was used along with historic locational marginal prices (LMPs) for one year to estimate net benefits (where "net" means amount remaining after accounting for charging and energy storage losses).

For this study, the cases investigated involved utilities located within the PJM (Pennsylvania, New Jersey, Maryland) Interconnection, Limited Liability Company (LLC) region. From the PJM website: [PJM] "...operates the largest wholesale electric market in the world. Our foremost responsibility is the safe and reliable operation of the electric transmission system to assure the reliable supply of energy from generation resources to wholesale customers."

Most importantly for this study, PJM also coordinates the wholesale electricity marketplace (capacity and energy) in and around Pennsylvania, New Jersey, and Maryland. The LMP prices used for the study and for the examples shown below are those that apply at a specific "node" within the PJM area.

It should be noted that the prices used are historical, not projections. For a more robust evaluation, price and volatility projections should be used. But, to the extent that historical prices are indicative of prices in the future, this approach gives the most reasonable estimate of current and future benefits.

Rather than estimating arbitrage benefits for a specific storage technology (with a specific round trip efficiency and storage duration), calculations were made for a range of efficiencies, from 30% to 90%, and for storage durations ranging from one hour to ten hours.

Energy Purchase and Sales Prices

Figure 1 shows a sample of LMPs for nine days in August 2001, including the day when demand peaked (Tuesday August 8th) outlined in Case 1.a. During that period, significant price volatility is clearly visible.

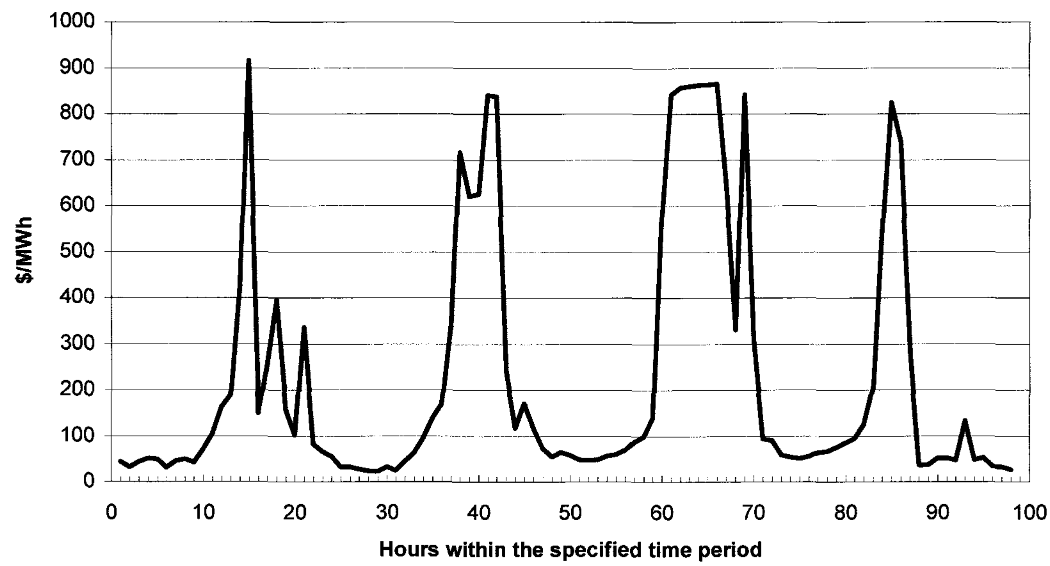

Figure 1. PJM Energy Price (LMP) Fluctuation for the Period of August 8th through August 12th, 2001.

Figure 2 shows prices for the entire year of 2001. Note that there are hundreds of hours when the price is above $100/MWh (10¢/kWh). During off peak periods (when storage plants could be charged) the price is frequently at about $30/MWh (3¢/kWh).

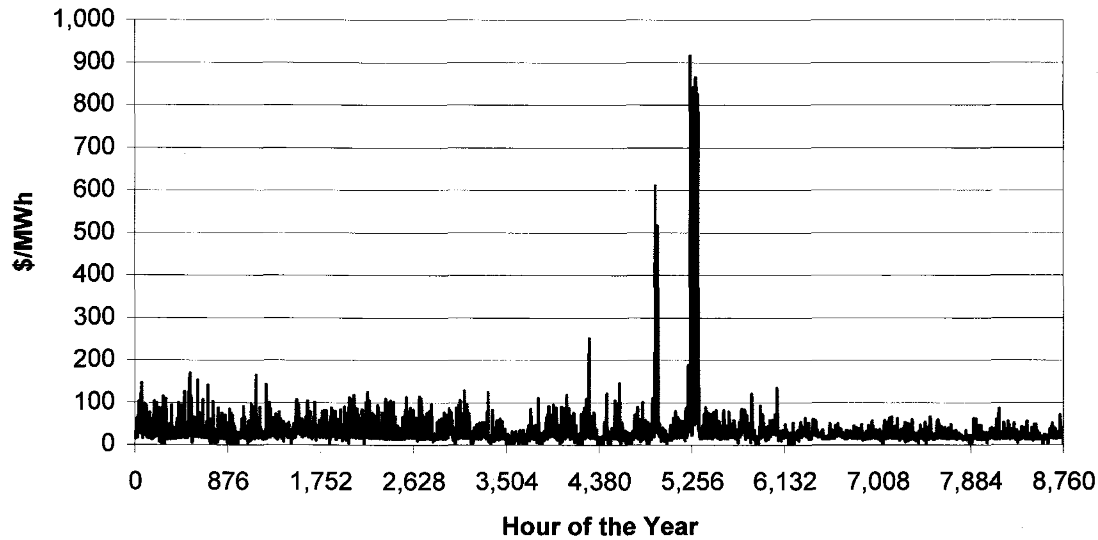

Figure 2. PJM Energy Price Fluctuation for 2001.

Appendix B provides more details on the average energy buy-and-sell prices.

Introduction to Estimating Annual Gross Benefits from Arbitrage

As a simple demonstration of the annual arbitrage benefit, consider a storage plant with 70% efficiency discharged for 1,000 hours per year during which the average price for on-peak energy is $100/MWh. Assume an average price for off-peak energy (for charging) of $30/MWh.

The average gross benefit from one hour of storage discharged on-peak is $57.1/MWh of "net benefit" (5.7¢/kWh). If 1,000 such "buy-low-sell-high" transactions are possible in one year, the total net benefit for arbitrage is $47.1/kW for one year.

Algorithm for Estimating Annual Benefits from Arbitrage

The estimate above of annual arbitrage benefits using an average benefit per transaction works fine as an illustration. However for a more accurate estimate, for a given circumstance, a more rigorous approach involving a storage dispatch algorithm is required.

The dispatch algorithm used for this study evaluates a time series of prices to find all possible "transactions" that yield a net benefit. It keeps track of net benefits from all such transactions for the entire year to estimate annual arbitrage benefits.

The arbitrage algorithm is described in detail in Appendix C. One key point regarding the algorithm used is worth noting: the approach used for this study yields results reflecting "perfect knowledge." That is, at any given hour in the year, the algorithm "knows" what prices will be at any other hour of the year.

In reality, of course, the price at a later time is not known. In a real situation the dispatch algorithm would have to include logic needed to forecast prices at a later time. Such logic is used to forecast electric supply and demand based on such criteria as historical loads, weather conditions, whether a given day is a holiday, weekday or weekend day, and the mix of loads being served.

Figure 3 below shows the incremental and cumulative annual gross arbitrage benefit for Case 2, (PJM prices 2001) for storage plants with storage duration ranges from one to ten hours. The bars indicate annual gross arbitrage benefits for storage plants that are 70% efficient.

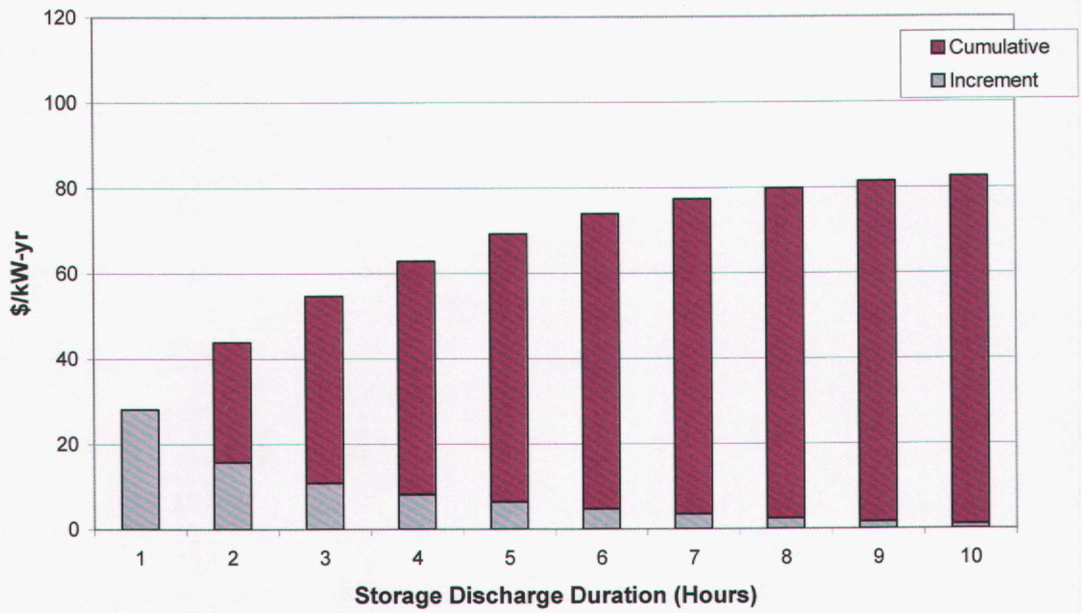

Figure 3. Energy Arbitrage: Gross Annual Benefits, 70% Storage Efficiency.

As hours of storage discharge duration are added to a storage plant, the total benefit increases and then begins to level off. That reflects diminishing benefits per buy-low-sell-high transaction (i.e., the average price differential diminishes as more and more transactions occur during the year.)

Annual Net Benefits from Arbitrage

The results above do not account for variable costs associated with energy storage. To do so, the dispatch algorithm must include the variable cost in the logic used to decide when or if to charge the battery. For this study the variable cost per kWh of energy discharged from the battery is assumed to be worth 1¢/kWh.

Consider the example described above: 70% efficient storage, 1,000 hours per year with an on-peak energy price of \$100/MWh, and average off-peak energy price of \$30/MWh. The average <u>gross</u> benefit from one hour of storage discharged on-peak is:

\$100/MWh – (\$30/MWh ÷ 0.7)
= \$100/MWh – \$42.9/MWh
= \$57.1/MWh (5.7¢/kWh)

When adding consideration of the variable cost, the <u>net</u> benefit from one average buy-low-sell-high transaction is:

\$100/MWh – (\$30/MWh ÷ 0.7) – \$10/MWh
= \$100/MWh – \$42.9/MWh – \$10/MWh
= \$47.1/MWh (4.7¢/kWh)

The *actual* incremental and total net benefits from arbitrage from a 70% efficient storage plant—after accounting for variable maintenance of 1¢/kWh, are shown in Figure 4 below. Energy prices used were those for PJM for the Case 2 locations in 2001.

Note that for a 70% efficient storage plant with three hours of storage, the total annual arbitrage benefit is about \$42/kW of storage plant capacity.

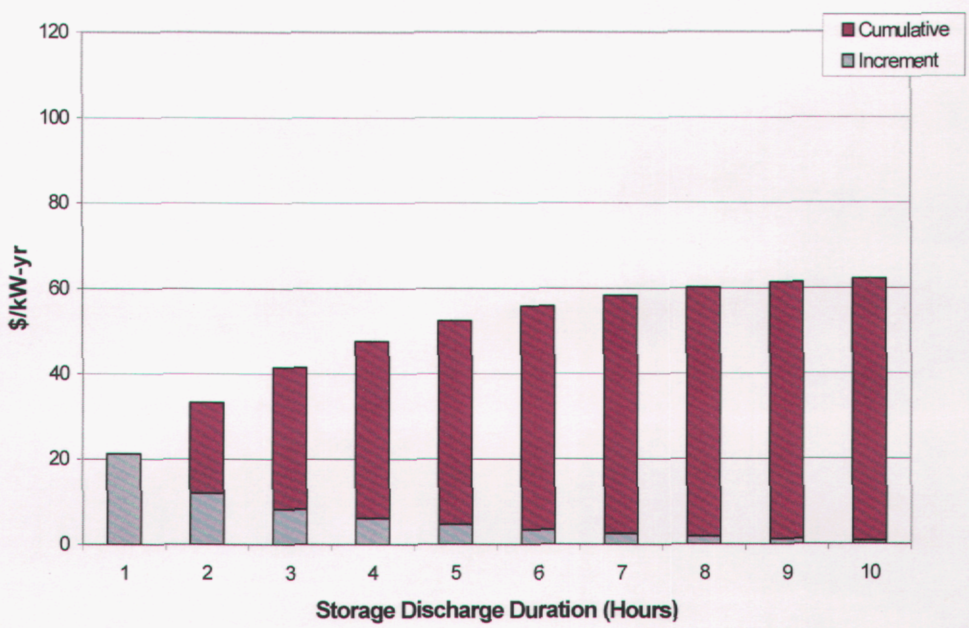

Figure 4. Energy Arbitrage: Net Annual Benefits for 70% Storage Efficiency.

Figure 5 below provides a summary of total annual net benefit from arbitrage transactions, for PJM LMPs for Case 2 in 2001, for plants with storage durations ranging from one hour to ten hours, and for storage plants with efficiencies of 30%, 50%, 70% and 90%.

As expected, as storage efficiency increases, annual arbitrage benefits increase. But notably, the difference between 70% and 90% is not large. Even 30% efficient storage yields substantial arbitrage benefits.

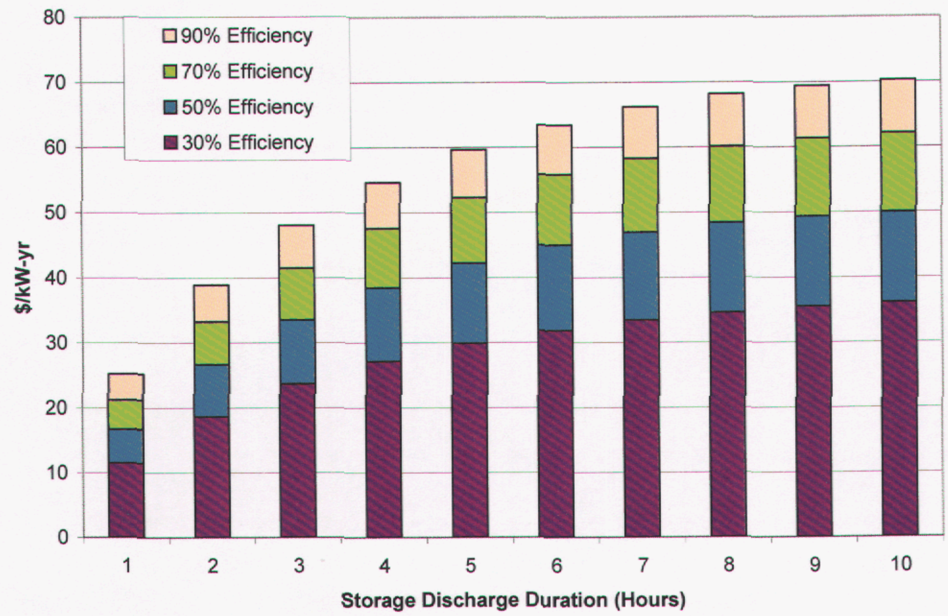

Figure 5. Energy Arbitrage: Net Annual Benefits for Various DS Efficiencies.

Life-cycle Benefits from Arbitrage

The values calculated above are for one year of arbitrage benefits. For this study the storage plant is assumed to have a useful life of ten years. To calculate net present value (NPV) of storage, an electricity price escalation rate of 2.5% (nominal) was assumed and a discount rate of 8% (nominal) was used.

Figure 6 below was used to estimate the NPV for ten years. To use that figure, first find the relevant number of years (storage life) on the horizontal axis, in this case, ten. Next find the point on the plot for the relevant discount rate (8% in this example) that is directly above the year. The intersection of that point (on the plot) with the horizontal axis, is the "NPV factor." Multiplying the one-year energy storage arbitrage benefit by that factor yields the life-cycle NPV of that one-year value for the given number of years (ten years in this example).

As shown in Figure 6, for an electricity price escalation rate of 2.5% (nominal) and a discount rate of 8% (nominal), the resulting NPV factor is 7.8.

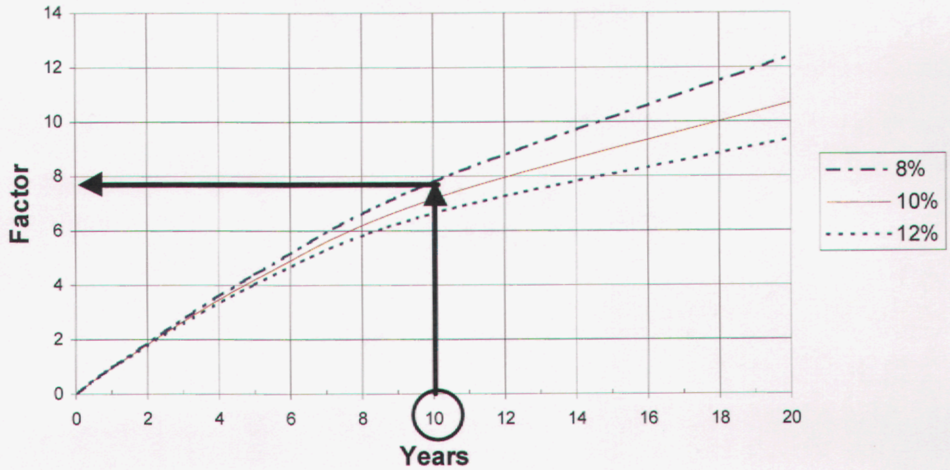

Figure 6. Net Present Value Factors (assuming a 2.5% price escalation rate).

Consider the example above: as shown in Figure 5, a one-year arbitrage benefit of $42/kW (in year one) accrues for a 70% efficient storage plant with three hours of storage. Multiplying $42/kW times 7.8, yields a net present value of $327/kW for a storage plant operating for ten years. Figure 7 shows life-cycle arbitrage net benefits for ten years, for 30%, 50%, 70%, and 90% efficient storage with discharge duration varying from one to ten hours.

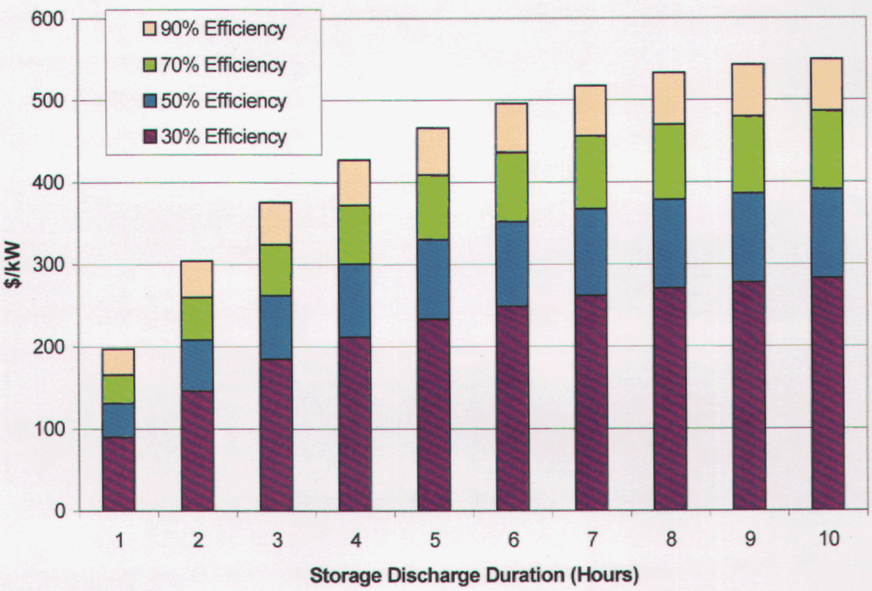

Figure 7. Energy Arbitrage: Net Life-Cycle Benefits for Various Efficiencies.

Transmission and Distribution Upgrade Deferral Benefit

Upgrade Deferral Benefit

Transmission and distribution (T&D) upgrade deferral benefits (deferral benefits) are the financial value associated with deferring a utility T&D upgrade for one year. For this study, it is also the financial benefit from storage if the storage is used so that a distribution upgrade is actually deferred.

The deferral benefit, for one year, is calculated by multiplying the utility cost of money (or cost-of-capital) times the total installed cost for the upgrade. Consider as an example a T&D upgrade that costs $1M. If cost-of-capital is 8%, then the one-year deferral benefit is .08 * $1M or $80K.

In other words, if a storage plant can be used such that the $1M project can be delayed for <u>one year</u>, the storage plant yields $80K in avoided cost. For this study, the benefit associated with use of energy storage to defer the upgrade (for one year) is assumed to be equal to that avoided cost. In practice, the entity whose investment is being deferred may or may not reward the owner of a storage plant, in part or in whole.

In general terms, locations for which distributed resources (DRs), including distributed energy storage, are best suited are those characterized by:

- "peaky" maximum load days (i.e., peak load occurs only during a few hours in a day)
- slow load growth
- T and/or D upgrades required are "lumpy" (i.e., for one or a few years a small amount of storage can defer a relatively large investment, for example, storage "modularity leveraging")
- high transmission access charges (that can be avoided with DRs)
- need for improved local power quality (PQ) that a DR can satisfy, hopefully with some specific, quantifiable monetary benefit

Storage Power Output Requirements

To defer an upgrade for one year it is assumed that the energy storage plant power output is equal to the expected load growth. Of course that assumption is ideal in this sense: this approach does not account for uncertainty, primarily: a) load may grow more than expected, or b) the storage may fail on peak demand days.

Consider the example above. Assume that the circuit is rated at 10 MW, and that engineers expect it to be fully loaded in one year. Load growth on the circuit is about 2% per year. Load growth is 10 MW * .02 = 200 kW.

So, a storage plant would have to deliver at least 200 kW to meet load growth so that the utility can defer the upgrade for one year.

Storage Duration for Deferral Benefits

This section is a brief description of the process used to estimate the storage discharge duration required for T&D deferral. Discharge duration is the amount of time that the storage plant must be able to discharge at full power.

Measured hourly demand data for respective cases is used to make the estimate. The hourly load profile for the day with the highest measured demand is isolated from the load data.

The maximum load on that day is treated as if it is the maximum rated capacity of the distribution system node being evaluated (demand ceiling). When load growth (for one year) is added to that day's load, by definition, the top of the modified load profile exceeds the demand ceiling. This is illustrated in the example in Figure 8.

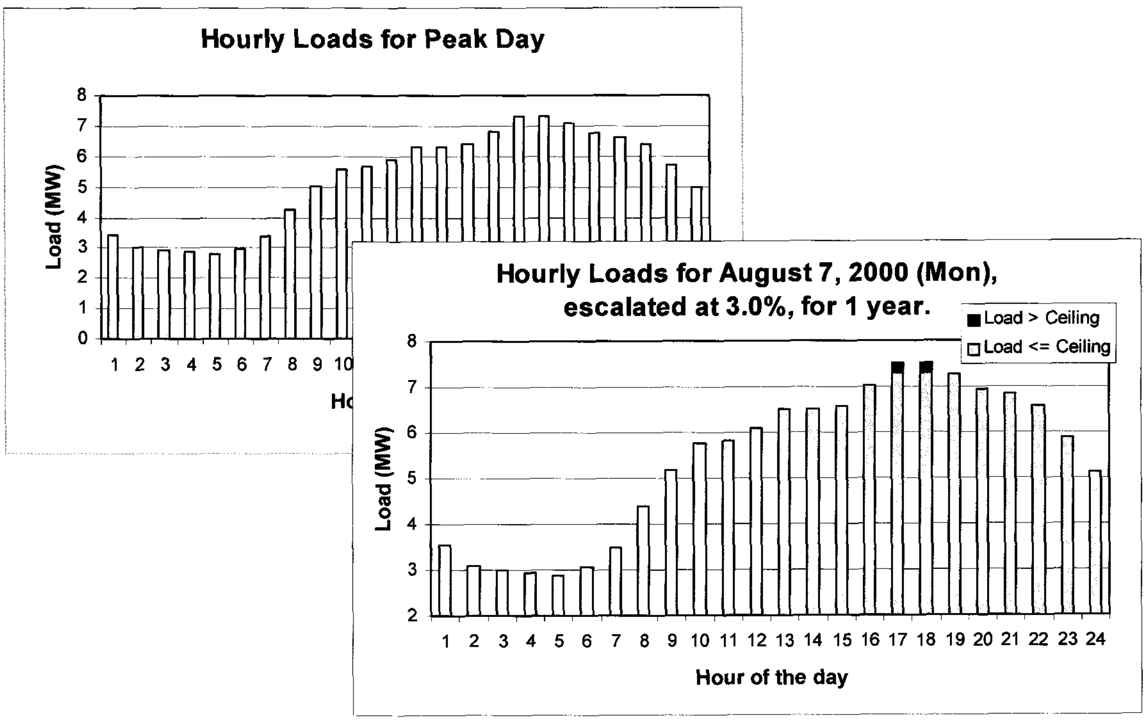

Figure 8. Storage Sizing to Meet Peak Demand: Power Requirements.

The number of hours during which load exceeds the demand ceiling is the storage duration. Even if the load ceiling is exceeded by just a small margin during a specific hour of the day, an entire hour of "full load" discharge is assumed to be required for the storage plant. This is intended to reflect conservative engineering design.

In the example in Figure 8, 3% load growth is added to the "year 0" demand profile. The result is that load in "year 1" exceeds the demand ceiling for two hours. That time period is assumed to be the storage duration required for this example. (See Appendix D for details).

It should be noted that this criterion is the minimum discharge duration needed to serve the T&D deferral application. It is possible that additional storage is warranted based on the incremental cost of the storage and the incremental benefit from additional energy arbitrage transactions. That circumstance was not evaluated.

Financial Benefit from Deferral using Storage

Continuing with the example above, the benefit for deferring the $1M upgrade for one year is $80K. A 200-kW storage plant with a discharge duration of three hours is needed. The storage deferral benefit is $80K/200 kW = $400/kW (that is, per kW of distributed storage installed).

Multi-Year Deferrals

It is important to note that for this study, storage capacity added in a specific year is credited with the deferral in that year only. If storage is used to defer an upgrade in subsequent years, the same evaluation described above (estimating the single year storage deferral benefit, storage capacity requirements, and storage discharge duration) is undertaken "on the margin" to determine whether the next year of deferral is cost-effective. Also note that if storage is used to defer a specific upgrade for more than one year, that storage capacity added in previous years must remain in place. That is, storage capacity used for deferral in subsequent years is added to the existing storage capacity, with additions sized to keep pace with load growth.

It is safe to assume that in almost all cases, at some point in time the upgrade will take place. If so, the storage can remain in place (for arbitrage) or it could be moved to another location for additional capacity benefits (plus arbitrage), as described in the next section.

Storage Redeployment and Portability

One way that a given storage plant could provide multiple years of distribution capacity upgrade deferral benefits involves moving the storage from one T&D hot spot to another. This, of course, requires that the battery system can be disconnected, moved, and reconnected, with modest effort and cost.

Even if this is done just once in the ten-year life of the storage plant, the impact on the cost effectiveness of storage can be dramatic. In the example above, storage provides a one-year deferral benefit of $400/kW of storage. So storage used for two similar situations, in different years, could provide benefits of $400/kW in year one and another $400/kW in the following year. Of course the benefits accruing in future years must be discounted to adjust for the time value of money before being summed. Though less likely, storage could also be used to address different winter and summer hot spots in the same year.

Calculating the Total Benefit

The arbitrage benefit and the T&D capacity deferral benefit are added to estimate the total life-cycle (discounted) benefits for storage use.

Arbitrage Benefit

The net annual and net life-cycle arbitrage benefits are shown in Figure 5 and Figure 7, respectively. From Figure 7, for a 70% efficient storage plant with a discharge duration of three hours, the life-cycle net arbitrage benefit is about $328/kW of storage over ten years of operation. For a 90% efficient storage plant the value is about $380/kW.

T&D Deferral Benefit

The cases investigated included using storage to defer T&D projects involving:
1) upgrading a circuit and adding transformers, 2) adding capacitors for reactive power, 3) upgrading transmission lines to an island, and 4) a generic hot spot characterization. The range of one-year deferral benefits estimated for the two participating utilities was between $75/kW and $900/kW of storage. See Appendix E for more details.

Total Benefits

Figure 9 and Figure 10 show the range of net life-cycle benefits for storage plants with efficiencies of 70% and 90%, respectively. A range of single-year deferral benefits ($75/kW, $400/kW, and $900/kW of storage corresponding to low, medium, and high) is shown as line plots. Those plots represent additions to the life-cycle arbitrage benefits shown as bars. Total benefits, for a given deferral benefit plus an arbitrage benefit for a storage plant with a specific discharge duration, is found on the Y axis.

From Figure 9 for a 70% efficient/three-hour storage plant, the life-cycle arbitrage benefits are $328/kW. If the T&D deferral value is $400/kW, the total life-cycle benefit is $723/kW for a 70% efficient storage plant. For a storage plant whose efficiency is 90% the total life-cycle benefit is about $770/kW of storage if used at a typical site, and about $1,200/kW of storage if used at a very valuable site.

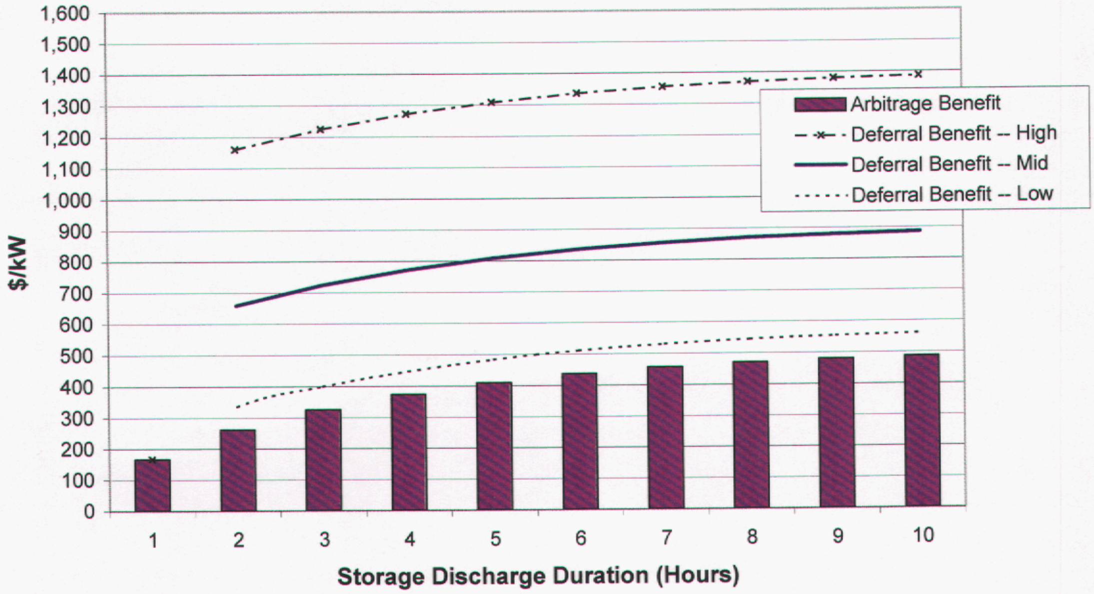

Figure 9. Total Net Benefit, 70% Efficient Storage Operated for Ten Years.

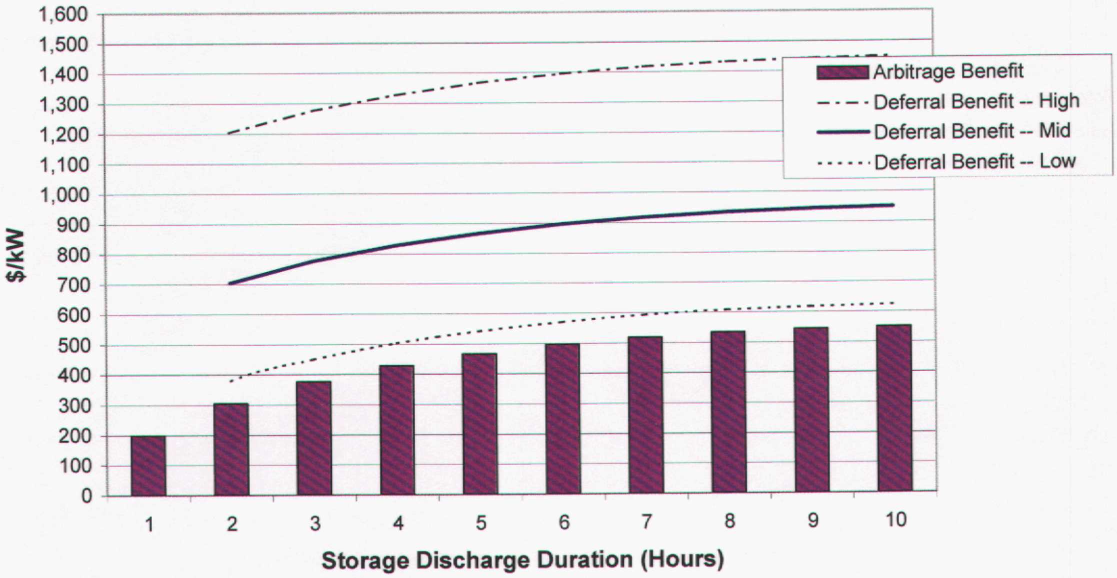

Figure 10. Total Net Benefit, 90% Efficient Storage Operated for Ten Years.

2.3. Storage Sizing

Power Output

In simplest terms, in any specific location for any given year, the storage plant power rating is based on the amount of load that would exceed the utility capacity if utility capacity is not increased. Based on the five cases evaluated for this study, the typical power output rating of storage that would be used for T&D deferral ranges from a low of about 200 kW to a maximum of 2 MW. Of course, that criterion will be driven by the location-specific circumstances being addressed with storage.

A few notes are important to consider. First, the small sample size does not provide a basis for establishing the actual range of storage plant sizes required for one-year T&D deferral. Specifically, plants with a rating that is less than 200 kW or larger than 2 MW may be required in any given situation. Conversely, the authors concluded that storage modules of about 200 kW seem to be indicated, based on the small sample considered.

Discharge Duration

The evaluation undertaken to establish the required storage plant discharge duration is described briefly in Section 2.2., above. More detailed evaluations are shown in Appendix D. Based on the load profiles used for the evaluation, storage typically must be able to provide for two to five hours of full load equivalent discharge to serve peak loads (i.e., for T&D applications).

However, it may be that the incremental arbitrage benefit from increased storage duration (beyond that needed for T&D deferral) exceeds the incremental cost. If so, vendors could choose to add to a plant's discharge duration to optimize total benefits. Using results shown in Figure 5, vendors can make innovative tradeoffs between cost, efficiency, and storage duration to maximize benefits.

2.4. Compatibility of Arbitrage and T&D Deferral Applications

For this study it was assumed that, in many cases, the same energy storage plant could indeed be used for both energy arbitrage and T&D upgrade deferral applications. That is, operation of storage for both of the primary benefits is compatible technically and operationally. The merits of that assumption were tested in two ways. First, a storage plants' technical characteristics needed for both applications were reconciled, as shown in Appendix F.

Next, possible financial effects associated with dispatch conflicts – between arbitrage and deferral applications – were evaluated. To do that, a "worst case" scenario was defined: assume that in order to meet local peak demand (to enable the deferral), the storage plant will not be available for arbitrage transactions during the ten hours of the year when the hourly arbitrage benefit will be highest (i.e., all benefits from operation for arbitrage during the ten most "profitable" hours in the year is subtracted from total arbitrage benefits estimated.)

Based on that exercise, the authors concluded that there is only a modest effect on total arbitrage benefits even if the storage plant is not allowed to discharge during all ten of the most valuable (energy price) hours of the year.

Section 3. Technical Product Requirements for Benefits

The two most important storage plant characteristics, power rating and discharge duration, were addressed in Section 2. Other key technical characteristics of DS are addressed in this section.

3.1. Approach Overview

A key step in the evaluation process for this study was a characterization of the technical requirements for energy storage. Requirements are those needed if storage is to be used for the individual applications under consideration. The primary applications, described in Section 2, include:

1. Energy price arbitrage (make/buy-low-sell-high)
2. Transmission capacity
3. Distribution capacity

The secondary applications considered include:

1. Ancillary services (nine types were considered)
2. Local power quality
3. Local electric service reliability

The first step in the process was to establish technical requirements for all potentially compatible individual storage applications listed above. Applications and application-specific technical attributes (required) are listed in a detailed matrix shown in Appendix F. Next, secondary applications with technical requirements that are not compatible with the three primary applications (listed above) were eliminated from further consideration. Finally, a "specification" was developed based on attributes for the primary applications, i.e., the specification is for a storage plant that can be used to serve the primary applications.

The specification was used during subsequent discussions with energy storage vendors as described in Section 4. Discussions involved the potential for vendors to provide systems with: 1) the technical attributes needed, and 2) a price that is comparable to or lower than the benefits estimated for DS used for arbitrage and T&D deferral.

3.2. Compatibility of Individual Applications

After considering the possible combinations of applications (that could be served by the same DS plant), the authors concluded that the three primary applications are compatible. Specifically, energy storage used to reduce localized peak demand for distribution and/or transmission capacity to defer a T&D investment can also be used for energy price arbitrage.

For this study, the authors concluded that what are generically referred to as "ancillary services" (described in detail in Appendix G) can generally not be used with these three primary applications. This is due in part to some technical incompatibilities, although the technical requirements for energy storage used for energy arbitrage or in lieu of T&D capacity are fairly similar to the requirements for most ancillary services. But most importantly, ancillary services applications cannot be served by a given storage plant at the same time that the storage is being used for the primary applications.

Operationally it would be difficult to provide both T&D "capacity" and ancillary services simultaneously. Since each ancillary service may be provided under strict contractual terms, failure to provide both T&D capacity and the respective ancillary service simultaneously is likely to make such contracts incompatible. Though spinning reserve is compatible technically with buy-low-sell-high and T&D deferral applications, storage cannot provide spinning reserve at the same time that it provides T&D capacity or energy arbitrage.

The remaining secondary applications – improved local power quality (PQ) and reliability – are circumstance-specific. Related financial benefits cannot be generalized easily and the operational compatibility of storage used for PQ and reliability applications has not been demonstrated.

Nonetheless, the benefits can be high, and in some cases, they may be additive with the benefits associated with the primary applications. For example, storage used primarily to defer a T&D upgrade could be located at the facility of a utility customer that requires especially high service reliability and/or power quality.

Please see Appendix A for the details about the evaluation of compatibility of the primary and secondary applications, and Appendix G for details about Ancillary Services.

Summary

It appears to be practical to use the same storage plant to provide T&D capacity deferral and for energy arbitrage transactions. It does not appear to be practical to also provide any of the ancillary services because they are likely to be required during the same times as T&D capacity deferral is needed and when energy sales are most profitable.

3.3. Storage Plant Specifications

Attributes included in Table 1 below are those affecting the technical viability of storage for targeted applications. Other attributes, such as system voltage and ramp rate (shown in section 3.4), include some that are typically specified for utility-grade storage. However, we believe that these other attributes either: a) do not affect cost or benefits, or b) are unimportant for storage used for the primary applications.

Some other important storage plant attributes are addressed as part of the cost/benefit assessment and are not part of the technical attributes. These include storage plant discharge duration, round-trip efficiency, and operation and maintenance costs.

Technical Requirements for T&D Deferral Drive the Plant Specifications

The authors concluded that storage devices which can perform well enough to satisfy technical requirements for utility transmission and distribution deferral could easily serve the arbitrage application. That is, the T&D deferral application has the more demanding technical requirements. So, the attributes shown in Table 1 – for distribution deferral – define the specification for the combined applications (arbitrage plus T&D deferral).

Table 1. Storage Plant Technical Requirements for Combined Applications

		Reliability			Power Quality					Communications and Control		Form Factor		
Application	Discharge Duration	Scheduled Outage Rate	Unscheduled Outage Rate	Performance Gaurantee (importance)	Voltage Surge/Sag Ride-through	Frequency Stability (+/- cycles/sec.)	Minimum Power Factor	Controllable Power Factor Range (max lag/lead)	Harmonics (THD)	"Flexible" Communications (importance)	Control (importance)	Floor Space (importance)	Portability (importance)	Modularity (importance)
Distribution Facility Deferral	3 - 4 hours	<50%	<.1%	High	+/-70%	.2	.90	.85 - .7	IEEE 519	High	High	Moderate	High	High

Technical Attributes

Discharge Duration

Discharge duration is the number of storage discharge hours required. It is included in the table for completeness. For a discussion of estimating this storage system attribute, see Section 2.

Reliability

Scheduled Outage Rate

This is the portion of the year (%) during which the storage plant may be taken out of service for routine/expected maintenance without significant loss of benefits.

Unscheduled Outage Rate

This represents the portion of the year (%) during which the storage plant may be out of service due to unexpected downtime.

Performance Guarantee (importance)

This criterion is an indication of the degree to which a performance guarantee is important if a storage device will be used for the respective application. In short, if a distribution and/or transmission engineer is to feel comfortable enough to specify storage in lieu of wires and transformers, he/she must be assured that the storage plant will perform when needed.

Power Quality

Voltage Surge/Sag Ride-through

This attribute involves the ability of the storage plant to ride-through voltage fluctuations of short duration (i.e., several seconds). It is specified in units of % of nominal.

Frequency Stability (+/- cycles/second)

Frequency stability indicates the variation of the output frequency from the storage plant.

Minimum Power Factor

Any device that provides application-specific service should maintain a power factor above this level during discharge and when charging.

Controllable Power Factor Range (max lag/lead)

For some applications, the storage plant could be called upon to provide reactive power (volts amp reactive–VAR). To do this, the storage plant must be able to adjust the degree to which current lags or leads the voltage.

Harmonics: Total Harmonic Distortion (THD)

Current harmonics that emanate from any device that interacts with the power grid are not desirable. This attribute is a quantitative characterization of the amount of total harmonic distortion that is permissible from the storage device. This topic is a subject of the Institute of Electrical and Electronic Engineer's (IEEE's) Standard 519 addressing Standard Practices and Requirements for Harmonic Control in Electrical Power Systems (http://grouper.ieee.org/groups/519/).

Flexible Communications and Control

The Flexible Communications and Control criteria were included on the original list of attributes considered. But, the authors' later concluded that there are no novel or exotic control or communications requirements, although these criteria are rated as highly important.

Form Factor

Floor Space

This criterion is the degree to which the storage plant's footprint is important for the primary applications.

Portability

This criterion is the degree to which it is important that storage equipment can be moved readily for the primary applications.

Modularity

This attribute relates to how practical it is to add power output (kW) or energy storage capacity (kWh) to a storage system. For this attribute, importance is specified.

3.4. Some Attributes Not Included in the Specification

Voltage

Storage plant output voltage was not considered to be an important criterion in this context because it is a criterion that is relatively easy to address for likely utility voltages.

Ramp Rate

This criterion is unimportant for arbitrage. For capacity applications including T&D deferral, it *may* be important. However, given the nature of the applications evaluated, the storage plant is treated as if it discharges at its full output rate during the hours when T&D capacity is needed (for deferral). So, ramp rate is not a criterion that is relevant.

Charge Rate

This criterion would be important for storage applications requiring long diurnal discharge durations. But, for the arbitrage/T&D deferral application, this criterion is not important because diurnal discharge durations tend to be around three to five hours. So, unless the plant has a very slow charge rate, it always has enough time to recharge between discharge events.

Start-up Delay

The authors concluded that there would be enough of an indication ahead of time (before the storage plant's capacity is needed–many minutes or even tens of minutes) for any storage technology to get up to rated output quickly. Therefore, the startup time is not a criterion that was included in the required attributes.

3.5. Storage Depth of Discharge for Benefits

Upon request, vendors were provided with information about the frequencies and durations for various depths-of-discharge levels, if needed, to assess the viability of their product. The useful life and the maintenance costs for some storage technologies are affected by these criteria.

That information is provided, graphically in Appendix H. It is provided for consideration by storage technology developers whose storage technologies are affected by depth of discharge. Those developers are encouraged to examine this information (in Appendix H) to determine whether charge/discharge patterns associated with energy arbitrage may affect storage system life.

Section 4. Vendors' Perspective on High Value Added Applications of Storage

4.1. Approach

Vendor participation and input was an important aspect of this project. Vendors were asked to validate the economic benefits, to affirm technical requirements and attributes, and to provide a check and balance as to the prospects for arbitrage and T&D deferral as a new opportunity. A description of the approach used and the vendor input received is provided in this section.

Participating Vendors

The participating vendors were selected based on the appropriateness of their technology for the storage applications under consideration and upon their willingness to participate. For example, technology vendors who were pursuing short duration, high power applications, often referred to as "power quality" applications, were not approached because this was inconsistent with the requirements of the high value-added combination application addressed by this study.

In addition to meeting the vendor selection requirements mentioned above, it was decided that a large conglomerate with significant manufacturing and market experience in supplying utilities with T&D equipment should be engaged. Further, such a company should be engaged whether or not that company was currently in the storage market so long as there was interest on the conglomerate's part. The decision to include this type of vendor is predicated upon the belief that for the identified markets to succeed on a large scale, there would have to be an evolution away from the past approach used to supply storage systems.

Storage facility development in the past has been characterized by a "project" approach involving considerable engineering, construction, and separate suppliers of large and key system elements. The high value applications identified in this study lend themselves to a much more "product" oriented approach, where the amount of engineering, for a given site, may be substantially reduced by building in a strategic amount of product flexibility. In this way, a given product can address a large number of multiple sites. This approach necessitates the integration and manufacture of the key elements into a product "platform" as well as significant up-front engineering. Large conglomerates are viewed as likely candidates to fill this need, should it materialize.

In all, four vendors were engaged and provided a significant amount of feedback. These vendors were: ZBB Energy Inc., Innogy PLC, Magtube Inc., and GE Power Systems Group. Other vendors who were engaged to a lesser degree were the Boeing Flywheel group, SAFT America, and C&D Technologies.

Attributes Matrix

As shown in Appendix F, the broadest range of possible "high value" applications for distributed energy storage was considered for this study. For each application, technical requirements were specified. Eventually it was determined that the arbitrage and T&D deferral applications were compatible and that the combination of possible applications provided the highest overall benefit from distributed energy storage. Ultimately the technical requirements for distribution deferral were determined to be the most rigorous (relative to those for arbitrage) and thus they were specified as the technical requirements for storage plants used for arbitrage and T&D deferral.

It should be noted that these technical requirements do not comprise an actual specification. They may be different for any specific circumstance. They were intended to be representative. They also contain criteria that vendors could use to determine, in general terms, whether they can provide storage with characteristics and costs needed to serve the arbitrage plus T&D deferral application.

Attributes were broken down into six broad areas including: reliability, response time, power quality, remote communication and control, form factor, and application ratings (such as number of cycles). Within each of the six categories, more detailed attributes were defined. The attributes matrix (shown in Table 1) together with a detailed explanation is provided in Section 3 of this report and a detailed matrix is shown in Appendix F.

Vendor Visits, Market Vision, and Questionnaire

There were two meetings per participating vendor. The first meeting was used to provide preparation and discussion for possible cooperation and to describe the study's general approach and background.

Following this first meeting, a document describing the detailed economic benefits of arbitrage and T&D deferral was provided. The information was a summary of Section 2 in this report. Included in the circulated document was a straw-person market vision and questionnaire. (Appendix I contains the questionnaire).

The vendors were asked to provide input on the market vision and to respond to the questionnaire in some detail. The questionnaire covered a broad range of topics including views, perspectives, and relevance of work to vendor activities. The questionnaire also focused on the vendor's perspective as to existing barriers in the developing market, as well as a look to the future to determine what is needed to break down these barriers.

4.2. Vendors' Responses

Through the meetings and using the tools discussed above, vendors supplied significant input on all aspects of the storage market study. As would be expected, there were differences in the input that often related to a particular vendor's technology or market vision. There were a number of universal reactions to the study, which are highlighted here.

Economic Analysis and Market Definition

Three of the four vendors interviewed reported that they have considered arbitrage and transmission distribution deferral as potential markets for their products. However, because of a dearth of data and necessary skills, they have been unable to clearly identify the economics and therefore, the value proposition, for these applications.

Crystalizing and validating the value proposition was cited as an important benefit of this study. Also, there has not previously been a good understanding of the compatibility of the two applications.

Ancillary Benefits

In general, there was resistance to accept the author's assertion of not accruing the secondary and ancillary benefits beyond arbitrage and T&D deferral. This assertion was used in the study after careful consideration of all possible ancillary benefits and how these benefits would impact the primary applications of arbitrage and T&D deferral. It was determined that DS system operation to serve these applications would conflict chronologically or contractually. For this and additional reasons cited in this report, ancillary services were determined to be incompatible (Appendix G provides details).

The desire to include benefits associated with these secondary applications are understandable as they add value to the storage proposition. And it is acknowledged that certain sites exist which would allow for the capture of the primary and some secondary benefits (especially local power quality and reliability improvements.) This is viewed as the exceptional case, however, and not the rule.

Efficiency

The relatively limited importance of storage efficiency for the combined applications was viewed with surprise by most vendors. Technology manufacturers have spent a good deal of capital, time and effort in trying to optimize efficiency of their storage systems only to find that efficiency does not significantly impact economic value. This insensitivity is clearly evident in the economic analysis of this report. Vendors are quick to point out, however, that efficiency is highly important in other applications such as the inclusion of storage with renewable energy sources, vehicle applications, and others. For these applications, efficiency improvement efforts do have merit.

Efficiency insensitivity does however, allow the vendor to look at their technology in a new light and to re-evaluate the efficiency/capital cost trade-off. This trade-off goes beyond the storage device and includes any components that are in series with the storage device. This includes balance of system items such as conductors, inverters, or transformers. There is a very definite relationship between initial capital cost and efficiency. This revelation caused the vendors to go back to their suppliers and extend this tradeoff into their supply chain.

Technical and Cost Feasibility

Each of the vendors agreed that their technology was capable of meeting the technical requirements needed for the arbitrage plus T&D deferral application. This was not a big surprise given that arbitrage and T&D deferral applications are not particularly demanding in terms of response time, form factor, or other technical requirements. Furthermore, all of the vendors indicated that they were capable of achieving the cost targets today as indicated by the benefits estimated for the combined arbitrage plus T&D deferral (i.e., they can produce systems with a price that is commensurate with the highest level of benefits estimated for this study).

This should not be surprising again since at the high deferral range, the "indifference" (economic concept that describes a customer's response to options) costs are quite high. All vendors felt they had realistic plans in place that would allow them to meet even the most aggressive (lowest value) indifference points over the course of the next few years. The basis for these cost reductions are both technical- and process-related.

4.3. Summary of Vendor Surveys

The participating vendors concluded that the combined applications of energy arbitrage plus T&D deferral provide significant economic value. The technical and price requirements for storage systems that can serve the combined applications are within reach today. Furthermore, storage technology continues to improve with technical and process improvements. Vendors were not willing to give up on ancillary benefits and thought that in many cases these could be captured over and above the primary applications. The role of storage device efficiency has been clearly identified for these primary applications and the study's results have pointed the vendors in the direction of re-evaluating their efficiency/capital cost trade-offs.

The bottom-line barriers to the development of this marketplace are seen as two-fold. One is the gap in the risk/reward structure between the vendors and the utilities that could use storage and the other is the utility industry's unfamiliarity with storage as a solution to generation and distribution shortfalls.

To address the risk/reward structure gap, it is believed that there will need to be certain warranties and guarantees in place before utilities will widely adopt the use of storage for T&D deferral. This is viewed as a difficult chasm in large part because of the unfamiliarity with the technology and application, and a lack of product reliability data at this early date. Neither party, storage vendor nor utility, is likely to take on sole risk in these applications early in market development, and it is expected that writing contracts acceptable to both parties will be challenging. This market challenge is seen as temporary, however, as familiarity with successful projects grows and the collection of field data grows, the uncertainty with applying storage technology should diminish. To address these immediate barriers, many of the suggestions for future work revolve around creating familiarity with storage devices through demonstration projects.

Section 5. Storage Market Vision

5.1. The Market Opportunity

Distributed Utility Associates has suggested an innovative market vision for distributed energy storage that combines two separate but compatible applications: 1) energy arbitrage, and 2) T&D capacity upgrade deferral.

The benefit stream from arbitrage is assumed to last for ten years (assumption is based on a ten-year life for the storage plant). Arbitrage benefits are available at any location connected to the grid that can gain access to the greater electricity marketplace. The magnitude of the arbitrage benefit is highest in areas with volatile electricity prices.

Transmission and distribution deferrals are area-specific. Deferrals occur only within utility transmission or distribution networks that are nearly overloaded. Furthermore, for this study the financial benefits associated with T&D deferral were assumed to accrue for just one year. Based on an evaluation undertaken for this study, the authors concluded that the two applications largely do not interfere with each other operationally. So, the same distributed storage system could be dispatched to earn benefits from both applications.

While other simultaneous benefit streams are possible, the combination of arbitrage and T&D deferral applications is predicted to provide a benefit of $500 to $1,000/kW for storage systems in the 250-kW to 1,000-kW size ranges, with discharge durations ranging from three to five hours. This assumes reasonable values of storage device efficiency, operation and maintenance costs, and historically-based electricity price levels and volatility. Several storage technology developers have suggested that they are now able, or soon will be able, to offer storage systems with a price that is at or near these levels.

The authors did not address the many possible follow-on uses for a storage plant after it has been used for one year of T&D deferral. There are many possibilities such as leaving it in place for continued arbitrage, moving it to a location with power quality problems, using it in subsequent years at other locations to defer other T&D projects, using it for ancillary services like spinning reserve[3], etc. (Please see Appendix A for details on these "secondary benefits.")

5.2. Market Potential (GW, GWh)

The storage system value was based on analyzing wholesale electricity prices and consumption patterns in the PJM area. Total peak load within the PJM territory is about 60 GW. This region was selected for analysis for three reasons:

- High electricity prices with high price volatility
- Publicly available electricity price data
- Interested utilities

If this region is indicative of another 20% of the remaining peak load in the U.S. (total of 700 GW[4]), then an additional 140 GW of market might be in play, totaling 200 GW.

Since the applications are meant in large part to defer load-growth-induced T&D investments, and since price volatility reduction is subject to saturation by too much storage installation, the market potential could conservatively be further reduced to just the load growth in the PJM region and the assumed 20% of the rest of the U.S., which is approximately 2% per year of 200 GW, or 4 GW per year.

The authors assumed a four-hour storage plant discharge duration that yields a 16-GWh market potential. For reference, approximately 20 GW of storage is already in place in the U.S. system (mostly in the form of pumped hydro) and total U.S. load growth is about 20 GW per year. Assuming a typical discharge duration of four hours, storage systems costing $1,000/kW (for power and energy components), the 4 GW/16 GWh of market potential per year represents a prospective annual revenue stream of $4B per year for the storage industry.

5.3. The Product

Product Characteristics

Since the arbitrage application is fairly independent of system scale, storage power and energy ratings would depend more on the characteristics of the transmission and/or distribution capacity to be deferred. Products that are modular (i.e., allow capacity additions as needed and are transportable) will have an advantage. Module sizes should be in the range of 100 kW to 1 MW, with two to five hours of discharge duration. Reliability of the storage systems would be assured by the supplier/installer and a performance guarantee/warranty offered.

Excepting demonstration plants, storage systems used for the combined application must be turnkey, perhaps even "plug and play." This includes compliance with all relevant standards such as IEEE P1547 (electrical interconnection with the grid) and IEEE 555 (harmonics).

A ten-year life is used as an underlying assumption for the arbitrage benefits calculated herein. This is somewhat arbitrary. In reality, a cost/benefit tradeoff would be made between the incremental cost to make the storage plant last longer versus the incremental benefit from the extra years of arbitrage benefits.

Portability may be important to the overall value proposition for distributed storage. If a storage plant is both "plug and play" and portable, there is significant potential to use it more than once for capacity deferrals in different locations. It also allows use of the storage for other applications (e.g., reliability and power quality) at the original site or other locations.

The authors contend that portability can add several hundreds of dollars per kW to a system's value over an assumed ten-year life if the storage plant is used in more than one location. Consider the hypothetical example shown in Table 2.

Table 2. Illustration of Transportability Benefits

Storage Plant Capacity (kW)	210			
Interest Rate	7.9%			
Discount Rate	10.0%			
Year #	1	3	5	
Load Growth Rate	2.0%	2.0%	2.5%	
Base Capacity (MW)	10.5	10	8	
Project Cost ($Million $Current)	1.06	2.5	1.5	
One Year Deferral Value				**Total**
$Current	83,740	197,500	118,500	**399,740**
$ PW	83,740	163,223	80,937	**327,900**
Load Growth (kW)	210	200	200	
Storage Deferral Value				**Total**
$/kW-yr, $Current	399	940	564	**1,904**
$/kW-yr, $PW	399	777	385	**1,561**

In that example, a 210-kW storage plant is used in years one, three, and five of its life, at three separate locations. Each deployment is done to defer a T&D upgrade for the respective location for one year. Deployments are worth $399, $940, and $564 per kW (of storage), respectively in those years. The total is nearly $2,000/kW ($1,561/kW net present worth (PW) value).

Portability also reduces risk because the storage plant can be redeployed if it: a) is not actually needed where it was originally deployed, or b) cannot provide sufficient value where it was originally deployed.

Summary of Product Characteristics

To participate in this emerging market, storage technology developers and system suppliers must offer field-proven, reliable, user-friendly, turnkey, modular (100 kW to 1 MW) storage systems.

Proven system reliability is most important for transmission and distribution deferral purposes, since a utility would almost certainly require a performance guarantee and perhaps even insurance against failure to operate during infrequent but severe local demand peaks. Utility engineers and regulators must have assurance that the storage plant will operate very reliably on command, or they would be assuming additional risks.

Furthermore, if distributed storage solutions require specialized engineering, construction, or installation, then utility engineers and regulators are unlikely to even consider storage. Especially for smaller scale projects, the "hassle" and related overhead cost must be very limited.

Though storage capacity may have to be as much as several MWs per site, 100-kW to 200-kW modules would be portable and flexible (can be added in increments, as needed to match T&D system load growth.) It appears that roundtrip storage efficiency is not a major driver of product viability (down to about 70%).

5.4. Possible Owners of Distributed Storage Systems

The most likely owners of such storage systems initially would be utilities. They have the best chance of being rewarded for T&D deferrals. Utilities that are most likely to embrace the concept are: a) those with an operations and planning structure that is driven by what is generically referred to as performance-based ratemaking (PBR), and b) municipal utilities (munis) or co-operatives (co-ops) that manage their bulk electricity costs while deferring T&D upgrades. Investor-owned T&D utilities (other than munis or co-ops) must have regulatory permission to use distributed storage for arbitrage and in lieu of T&D capacity upgrades, before significant deployment of distributed storage may occur.

Eventually, Energy Service Companies (ESCOs) or Energy Services Providers (ESPs) will also enter this market, once the rules become more certain, especially regarding interconnection and utility roles. Energy Service Companies may be a significant "market maker" for distributed storage if they can negotiate with the T&D utility such that the utility is willing to "reward" the ESCO for allowing deferral of T&D investments.

End-users/energy customers could also participate in this market, especially if: a) reliability and/or power quality are important concerns, or b) electric tariffs provide compelling time and location dependent price signals for energy and/or demand. The authors contend that electricity end-users for whom distributed storage may be most viable are those: a) with relatively large demand (at least tens of kW), b) with which the utility can and will share a portion of the T&D deferral benefits, and c) that have access to the electricity marketplace (for arbitrage).

State-specific regulations affecting viability of the respective ownership schemes described above range from those that encourage some or all of them, to those that discourage all of them. Many state's regulations are largely silent with regard to any or all of these ownership propositions. This makes generalizations about market feasibility difficult, and beyond the scope of this phase of the study.

5.5. Non-Storage Alternatives

For this study, distributed storage systems were compared to the grid. In reality, other distributed resources would also compete for some or most of the same load. Distributed generation is a strong competitor; leading options include small reciprocating engines and gas turbines. Eventually fuel cells might be used in these applications also. Another competitor may include demand management techniques including geographically targeted interruptible/curtailable rates.

So, the ultimate price point set by distributed storage systems vendors will be influenced by the life-cycle cost/benefit relationship for all competing solutions that can provide power for T&D deferral.

The key advantage that storage and all distributed resources have over T&D solutions is modularity. Transmission and distribution upgrades are usually installed in large increments whereas, in any given year, the only amount of new capacity needed is equal to one year's load growth. Conversely, distributed resources are modular: they can be added little by little as load grows. This T&D investment, known as "oversizing," gives modular, distributed resources a distinct advantage "on the margin."

For example a 10-MW distribution feeder growing at 2% per year will frequently be upgraded by 5 MW, far in excess of the 200 kW that is immediately needed (2% load growth per year * 10 MW).

Storage has some unique advantages relative to distributed generation technologies. Depending on the generation mix in the grid electric supply system, storage may provide advantages over distributed generation options. For example, assume that a central peaking generator's fuel efficiency is 30% and that the fuel efficiency of baseload generation is that of a new combined cycle plant, about 48%. For 80% efficient storage, the on-peak "efficacy" of the storage is 48% * 80% = 38%. That is a full 8 percentage points more efficient than the central peaker. This example ignores effects associated with T&D losses, which would also favor storage.

There is a similar relationship for energy cost. Consider a DG system that can produce energy for 7¢/kWh (incremental) including fuel and O&M. Compare that to storage with a variable O&M of 1¢/kWh, that is 80% efficient, using charging energy with a price of 3¢/kWh. For storage, the incremental cost per kWh of output is 1¢/kWh + (3¢/kWh/0.8) = 4.75¢/kWh. In addition, for storage (relative to generation) there is no need for fuel storage or for black start capability, and storage plants have little or no air emissions.

5.6. Defining Market Success

Market success would be measured by the fraction of load growth, in fairly volatile electricity price areas, for which storage is considered and adopted as the solution. The first step toward success could be a demonstration plant of 250 kW to 1,000 kW, located within a utility distribution system that is dispatched for both benefit streams. Reliable and trouble-free operation for one or two peak demand seasons would be a technology success.

A second such demonstration with either a second storage technology, or a larger scale (power) system would be an important second indicator of success. The market would be well on its way after a dozen such plants had successful demonstrations.

A mature market would have two or more storage system vendors competing for shares of a billion dollar per year market. Pre-engineered modular systems would be available for delivery on three to six month product delivery cycles. The ability to modularly upgrade existing systems would also be a sign of market and vendor maturity.

5.7. When Could This Market Realistically Develop?

The concept of using storage for energy arbitrage or for T&D deferral is not new; but pursuing them in combination, with the same storage plant *is* new. This "newness" will slow the pace of market development for the combined opportunity.

The effort to develop storage projects with both benefits streams will be mostly due to the novelty of using storage for T&D deferral. As the deferral market matures over the next five years, win-win opportunities like this will become more obvious and market entry should accelerate.

Bellwether signs from the electricity industry that this market opportunity could be ready to approach the potential indicated above would be:

- state regulators insisting that distributed resources (such as storage) be considered as alternatives for all wire upgrades.
- continued wholesale electricity price volatility in a free and open marketplace.
- the use of "de-averaged" electricity rates (i.e., electricity tariffs that reflect time-of-use and place-of-use).
- declining electric service reliability.

The pace of energy storage technology and energy storage system development will be up to the manufacturers, but positive storage industry indicators would be:

- participation of storage technology developers in distributed energy resource market development efforts such as IEEE P1547 and related interconnection standard-setting activities.
- development of storage products targeted at applications requiring low initial cost by trading off cost with efficiency.
- offerings of packaged and modular systems in the 100-kW to 1-MW range.
- demonstrations targeted at utility grade applications.
- the availability of strong warranties and guarantees.

In the absence of any of the above, the markets for combined arbitrage and T&D deferrals will be slow to develop, and will probably be limited to demonstrations of the technical feasibility in the near term.

Section 6. Market Challenges

6.1. Introduction

Several market challenges affecting the prospects for widespread use of energy storage for arbitrage plus T&D deferral are described below. They include:

- Perceptions
- Distributed energy storage's limited record
- Technology cost and performance
- Operational challenges
- Estimating and sharing benefits
- Competitive challenges from distributed generation and utility pricing

6.2. Perceptions

A key to the development of any market is based on the market's perception of the benefit versus cost relationship (value), and about related risk. Even if the financials are good, misperceptions may drive decisions. This is especially important for an emerging technology that is to be used for a previously untried application.

Key stakeholders that must be convinced of the value of DS include: utility engineers, financial decision-makers, regulators, insurance and banking industries, and local governments that may have to permit the equipment. Taking steps to reduce prospective users' perceived risk is an important next step toward development of the market for storage for the arbitrage plus T&D deferral application.

6.3. Distributed Energy Storage's Limited Record

Energy storage for arbitrage is somewhat familiar to potential users although most of the historical experience involves larger storage plants. However, there is limited experience with energy storage for T&D applications. As a result, distributed storage is, to a large extent, still a novelty to most utilities.

There is a significant record of successful operation of battery systems that are similar to those needed for the arbitrage plus T&D deferral application. Nonetheless, technology risk – perceived or real – affects perceptions about suitability of distributed storage for T&D applications.

Before widespread adoption of storage for arbitrage/T&D deferral is likely, a fairly broad spectrum of stakeholders will need to know more. Some of them are: utility financial and accounting decision-makers, and engineering decision-makers, utility regulators, and government agencies with jurisdiction over matters such as air emissions, building codes, fire and operational safety, noise, and zoning.

For example, before widespread adoption will take place, energy storage systems must be in compliance with the National Electric Code before local fire marshals will allow a facility to be used. This is especially troublesome if there is uncertainty about which codes and standards apply, as may be the case for new technologies.

Given the foregoing, there is a need to provide more evidence that: a) using energy storage for arbitrage plus T&D deferral is practical, safe, and environmentally sound, and b) energy storage technology is sufficiently reliable. Evidence requires demonstrations.

Demonstrations are also needed before insurance, accounting, and tax related protocols can be developed. For example, residential or commercial distributed storage system owners may violate provisions of their insurance policies or may not be able to recover damages if storage equipment malfunctions.

Demonstrations would also provide information about the effect of energy storage equipment related to noise, impacts on air quality, and aesthetics. Demonstrations would also address possible safety concerns such as operation and use, storage of hazardous materials, or generation of hazardous waste.

6.4. Technology Cost and Performance

High cost (equipment, operation and maintenance) is an obvious barrier to significant market use of storage for arbitrage plus T&D deferral benefits (Appendix E). Although each circumstance is different, based on study findings:

- Low capital cost and high reliability are much more important than round trip efficiency for the combined arbitrage plus T&D application. An installed system cost of about $1,000/kW for four or five hours might be inexpensive enough to earn market share.

- Variable operation and maintenance cost of one cent per kWh is low enough for storage to be cost-effective for highly volatile price situations.

- One potential problem for some types of batteries used for energy arbitrage is that frequent deep discharging may increase O&M substantially.

6.5. Operational Challenges

Even if the storage device can be built at a cost well below current prices, *operation* of such systems for arbitrage plus T&D deferral may not be straightforward.

Arbitrage

For this study, the arbitrage benefit was estimated with a dispatch model that uses historic energy price data; the result was that dispatch was performed with perfect knowledge about the future.

In reality, decisions about storage plant operations (charge and discharge) must be managed either by humans or by programmed control logic that can make hourly or even minute-to-minute decisions. If people must make such decisions, especially if numerous storage plants must be controlled, the cost could be prohibitive. So it will likely be important to develop control logic, perhaps involving artificial intelligence.

Transmission and Distribution Deferral

Based on actual load data from two utilities in the PJM area, estimating the magnitude of local peak demand (demand that will exceed the T&D node's load carrying capability) is relatively easy. Furthermore, based on typical utility operational criteria (primarily weather-related), it may even be possible to predict when peak demand may occur. As a result, the authors contend that dispatching storage to defer T&D upgrades is less challenging than dispatch for arbitrage benefits.

To be specific, the authors concluded that it would be fairly easy to determine for which days there is a ten percent or greater chance that demand will exceed load carrying capacity of the T&D node. For those days, the storage plant must be fully charged and ready to serve load (discharge) before the peak demand occurs. Also, for those days, the storage is discharged only to keep the net loading on the respective T&D node below its load-carrying limit.

Electrical Effects on Transmission and Distribution

There is very limited experience with operation of distributed resources (including storage) on specific T&D nodes involving: a) several or many distributed resources, or b) distributed resource capacity that is a large, or even a modest portion of the total load being served by the respective T&D node.

Important knowledge needed includes:

- practical limits to the portion of transmission capacity and the portion of utility distribution capacity that can be served by DR capacity;
- the types and level of protection needed for DR interaction with the grid and related costs;
- possible effects on grid power quality and reliability.

These issues are currently being addressed by the greater DR community. For more about that, readers should refer to the Department of Energy's web site for the distributed energy resources program and for the distributed power element of that program.[5,6,7]

6.6. Estimating and Sharing Benefits

There are many potential barriers to obtaining (monetizing) the benefits one might calculate for storage systems. They are not insurmountable, but neither can they be ignored.

Utility Cost Allocation

- Local utility avoided costs (generation, transmission and distribution credits can be offered, shared, or withheld).

- The mechanisms and degree to which costs associated with utility service reliability are allocated among customers, and/or how benefits (i.e., from additional DRs) are shared between the utility and their customers.

- Regional capacity value situation (capacity shortage versus oversupply).

Utility Pricing Mechanisms and Strategies

Though not the subject of this study, it is conceivable that energy storage could be purchased by utility customers, perhaps in partnership with utilities. Customers could use it to reduce electric bills and/or for more reliable, higher quality electric service. Utilities could encourage customers to do this – to defer T&D upgrades – with financial incentives.

At present, some utilities adjust customer rates or terms and conditions (for service) to discourage customers from installing distributed resources. This can be done several ways such as through the use of standby charges, exit fees, net metering provisions, distribution uplift or delivery charges (for energy sent to other customers), demand charge ratchets, long daily peak demand periods, and "full requirements" contracts.

Uncertainties in the New Electricity Marketplace

An underlying premise for this study is that energy price volatility will continue. Though that seems likely, given existing information, it is possible that energy price volatility may moderate. If so, energy arbitrage benefits will diminish.

Transmission capacity additions are uncertain. Congestion charges, in one form or another, seem likely in some regions of the U.S. (unless transmission capacity is added). Many utilities are hesitant to make large transmission or distribution investments until: a) related federal and state regulations are developed or clarified, b) regional transmission operators (RTOs) are in place, and c) other sources of "regulatory uncertainty" are addressed such as interconnection and pricing of services for customers with DRs.

6.7. Competitive Challenges

Distributed Energy Resources

Storage will have to compete with the electric grid and with other distributed resources for the arbitrage plus deferral application. Technological breakthroughs are accelerating for several distributed generation technologies that might compete with storage in any given circumstance. Leading distributed generation options are fuel cells, microturbines, and advanced reciprocating engines.

For the near future, the key competition from distributed generation would seem to be from advanced reciprocating engines. They are relatively inexpensive (per kW) and fuel efficiency and air emissions are improving. The key challenge for storage is that it tends to cost more per kW than engines. The effects include a need to obtain more capital up-front to purchase the storage equipment, annual financing payments are higher, and financial risk is higher. Owners of the more expensive equipment may be subject to higher property taxes and higher insurance premiums, per kW.

Utility Pricing Solutions

As described in Section 6.6. Estimating and Sharing Benefits, utility pricing is an important factor affecting the attractiveness of distributed energy storage for T&D deferral. In this case, utility pricing could become a competitor to energy storage.

It is a well-established practice for utilities to use geographically targeted pricing to affect customers' behavior. If targeted at areas that are downstream from grid hot spots, such pricing could be used to reduce load and thus defer the need for additional T&D capacity. Options include interruptible or curtailable tariffs, demand charges, time-of-use energy pricing, and "capacity payments" for controllable loads.

Section 7. The Plan – "Enabling and Facilitating" Market Development

7.1. Key Market Challenges

The market for distributed storage for the proposed high value utility application – arbitrage plus T&D deferral – does not presently exist; it must be developed. The use of *distributed* energy storage for arbitrage or for T&D deferral is quite rare. Neither is regarded as mainstream.

Because of this dearth of experience, the marketplace for distributed storage requires development. The items listed below are factors that are being addressed or will have to be addressed before there is significant proliferation of distributed storage for the arbitrage plus T&D deferral application.

However, it seems likely that there are enough opportunities with high value that some projects could be developed now, before a more mature market can exist. Though rare, there *are* organizations on the front line of the utility infrastructure that are willing to test the concept.

Some of the items described below are generic to all distributed resources (especially distributed generation). Others are specific to the arbitrage plus T&D deferral application. Some of these issues will be resolved over time by other technologies. Some issues require attention specifically by the energy storage industry.

Market Development Challenges Generic to Distributed Resources

This section describes a few key challenges facing distributed resources that also affect prospects for distributed storage. The items listed are, to one extent or another, being addressed by the distributed generation industry. They are topics that the storage industry should monitor. And, as appropriate, the industry may seek to influence related developments and/or to leverage related activities (e.g., development of interconnection rules).

Regulatory Acceptance of Distributed Resources

The distributed resource concept is becoming an accepted alternative to the conventional means for delivering electric utility services, but the process has a long way to go. There is a need for more experience and a compelling characterization of benefits and costs before regulators will accept distributed resources as a "mainstream" solution.

Utility Risk and Reward Sharing Mechanisms

It seems likely that there are many cases for which distributed resources may be the lowest cost alternative (for serving incremental capacity needs). However, existing engineering and business practices, biases, and regulatory provisions lead utility engineers and planners to favor the conventional grid alternative; in this case, addition of transformer and wire capacity far in excess of what is needed when the existing capacity first becomes overloaded.

Utility Electrical Engineering and Interconnection

Any distributed resource that actually injects electrons into the grid must satisfy existing rules and practices regarding electrical protection, grid interconnection, and safety. Because distributed resources are still rare, there is limited experience with the electrical implications of their use. Furthermore, design and electrical engineering tools (e.g., for circuit analysis) that address the impacts of distributed resources do not exist, for the most part.

For distributed storage perhaps the most concrete manifestation is the interconnection issue. Various states already have, or are developing, grid interconnection standards that will affect prospects for storage. To date, most address only generation. Coordinating with those efforts is important for the energy storage industry in general, and particularly if the arbitrage plus T&D deferral application is to become practical.

Siting

Because distributed storage is so unfamiliar, in any specific locale there may be reluctance to permit it. If there is even a remote possibility that distributed storage will be considered a hazard or a nuisance, even based on unfounded perceptions, storage developers may find that it is difficult or even impossible to get a plant sited and permitted. One manifestation of this challenge could be requirements for expensive environmental impact reports.

Market Development Challenges Specific to Distributed Storage

Need to Demonstrate the Application

Currently there is a compelling need to demonstrate distributed storage used for the arbitrage and T&D deferral application. Demonstrations are the necessary first step toward establishing a track record, so utilities, regulators, insurers, and local permitting agencies know that storage performs well.

Accepted Method Needed for Determining Storage Plant Size

Though adequate for a policy or high level evaluation, the methodology used to size the storage systems for this study is not adequate for actual design. Approaches used to estimate distributed storage power requirements and discharge duration for actual projects will have to be more robust. More importantly, they will have to be accepted by utility power engineers and regulators.

Accepted Method Needed for Estimating Direct Financial Benefits

The methodology used to estimate both arbitrage and T&D deferral benefits would have to be accepted by utilities, regulators and project financiers before it can be accepted as "mainstream." If the methodology is accepted it will have to be formalized. If it is not acceptable, a methodology that *is* acceptable will have to be identified and/or developed.

Limited Choice of Storage System "Products"

Though commercial grade distributed storage subsystems are available, few distributed storage systems are in use and some subsystems may still require development for the arbitrage plus T&D deferral application.

Besides technical specifications, a commercial grade product will have to allow for plug-and-play operation and must be fully supported by the vendor. Products must be easily deployable and must come with performance guarantees and warranties.

Communication with Electric Utility Systems

Currently, electricity supply and transmission and distribution systems do not have the necessary communication equipment for arbitrage to be a plug-and-play proposition.

Distributed Storage Controls and Storage Dispatch Logic are Needed

Though distributed storage controls will be similar to those for distributed generation, there may be some development needed to standardize distributed storage for the arbitrage plus T&D deferral application. Presumably the energy storage industry and the controls industries will address this need.

A need related to distributed storage control is for robust, straightforward logic for dispatching distributed storage for the arbitrage plus T&D deferral application. By itself, dispatch for T&D deferral is relatively straightforward. The control logic to dispatch for arbitrage is not so straightforward. Combining the two is an important challenge.

Limited Understanding of Possible Air Quality Benefits from Distributed Storage

It is possible for energy storage in general to have a positive impact on air emissions (locally and/or regionally). Various ways that the use of storage can reduce air emissions include: reduced (net) transmission and distribution losses, fewer power plant start-ups, reduced use of dirtier, less fuel-efficient peaking power plants, and reduced cycling of central power plants. However, limited research has been done to investigate the potential benefits, especially for *distributed* energy storage.

7.2. Needed Research

There are a number of ways that additional research can facilitate the acceptance of distributed storage. One way is to assist the storage industry to better understand utilities' interest in and concerns about distributed energy storage. Another way to facilitate market development is to help utilities gain a better understanding of distributed storage's potential benefits and how to pursue them.

Another potential research role is facilitation of utility-vendor demonstrations by undertaking "screening level" evaluations with utilities. The objectives of such evaluations would be to: a) provide opportunities for vendors to learn more about utility needs and perspectives, b) develop a framework for estimating project-specific estimates, and c) identify attractive hardware demonstration opportunities. It would also be valuable to catalyze development of standards or models for: 1) utility evaluation of distributed energy storage financials such as estimating costs and benefits, 2) plant performance, especially power quality and reliability, and 3) performance guarantees and warranties.

In pursuing these tasks, research would help to better define the possible benefits from, and market prospects for, win-win partnerships between utilities and customers involving use of energy storage for mutual additive benefits (i.e., to reduce customer utility bills and to defer T&D upgrades).

7.3. Market Development Plan

Plan Scope and Goal

The goal of a market development plan is to catalyze the market by addressing key challenges to market development for distributed storage (for the arbitrage plus T&D deferral application), i.e., challenges that are not being addressed by the distributed generation industry.

Plan Elements

Demonstration #1

There is a need to coordinate stakeholders including state energy programs and regulators, vendors, utilities, and electric service companies (ESCOs) to design and install the first-of-a-kind distributed storage system for the arbitrage plus T&D deferral application.

The demonstration plant would be sized between 250 kW to 1,000 kW for four hours. It would be located within a utility distribution system and would be dispatched for both benefit streams (arbitrage and T&D deferral).

Demonstration #2

A second such demonstration for a case with circumstances favoring the distributed storage option would also be needed. It would be: a) a second (different) storage technology, and/or b) a larger scale (power) system.

Define Elements of a Robust-though-Straightforward Storage Plant Sizing Methodology

Before utility engineers can embrace distributed storage for T&D deferral they must have a robust methodology for determining the appropriate power and discharge duration for a given location. Without it they are not likely to feel comfortable with distributed storage at all, or, they may resort to plant oversizing, leading to reduced value per dollar invested in the storage plant. Development of the methodology would be done in consultation with utility power engineers, regulators, and vendors.

Validate Method for Estimating Direct Financial Benefits

An important milestone for development of the arbitrage plus T&D deferral market would be to validate or refine, and formalize the methodologies used to estimate both arbitrage and T&D deferral benefits. This would be done in consultation with utility power engineers, financial decision-makers, and regulators.

Next Step

Ideally, demonstrations one and two would occur within 18 months and 30 months, respectively. The first steps are to identify potential partners and to scope out prospective sites (including storage plant size requirements and financials). The next step is development of a specification for the plant for vendors.

Plan Success Criteria

Demonstration Plants #1 and #2

Technical success associated with the two demonstration plants will be reliable and trouble-free operation for two peak demand seasons.

Market Acceptance

One important institutional indicator that the marketplace is developing would be that distributed storage is treated as a technically and financially viable option by utility power engineers, financial decision-makers, and by regulators. Success could be defined as the conditions outlined above in states representing twenty percent of U.S. peak demand, within four years. Preferably, the twenty percent corresponds to states with conditions that favor the arbitrage plus T&D deferral application, or at least the T&D deferral application alone.

Market Growth

The market would be well on its way after a dozen such plants have worked well. Specifically, market success would be indicated by ratings for plants in service totaling two to five MW, and six to 20 MWh of storage used for the combined applications within four years.

Follow-on Market Development

Coordination with Distributed Storage-related Developments in the Distributed Generation Marketplace

Because so much activity affecting prospects for distributed storage is being undertaken by distributed generation stakeholders, it is important that the energy storage community learn important lessons from those activities. The energy storage industry should also do what is necessary so that rules, regulations, and standards for distributed generation can accommodate energy storage.

Specific topics to monitor include: utility and regulatory acceptance and treatment of distributed generation, electrical effects on utility grid systems, interconnection rules and practices, benefits assessments, and siting.

Scope Out a "Model" Product

One possible way to encourage the market for distributed storage for arbitrage plus T&D deferral would be to develop a model design. Not only would it serve as a technical specification, but the process of developing the model would also be an important forum for various stakeholders to learn about other perspectives. Participants would include utility engineers and financial decision-makers, regulators, vendors, and possibly representatives of building permitting agencies.

Energy Storage Design Assistance Center

One possible way to provide stakeholders with necessary information and perhaps even evaluation methodologies and tools is to establish an Energy Storage Design Assistance Center for utilities, ESCOs, and utility customers, with a mission that is similar to the design assistance center established by Sandia National Laboratories for photovoltaics.

Develop Models for Risk and Reward Sharing

A promising way to empower utilities to take advantage of distributed resources and distributed storage in the near term is for regulators to allow utilities to share related rewards with customers who are willing to share some of the risk. For example, a utility would be allowed to give a rebate to customers that agree to cut their peak demand if the storage plant fails. So instead of the utility taking all of the risk related to storage plant failure, they share it. The quid pro quo would be a rebate or a credit on the customer's bill.

In fact, utilities already do something similar. They use what are called interruptible or curtailable (I/C) tariffs. However, this is rarely done at the distribution level. Traditionally I/C rates have been used for supply system capacity (generation or power purchases).

One possible way to catalyze market development for distributed storage would be to survey existing utility practices for such risk and reward sharing. Depending on findings, including gaps that affect prospects for distributed storage, the next step would be to develop models for establishing geographically targeted I/C rates, credits, and rebates that enable cost-effective distributed storage.

Investigate Use of Distributed Storage for Arbitrage plus Ancillary Services

As noted elsewhere in this report, distributed energy storage could be used for ancillary services. In fact, use of distributed energy storage for ancillary services may be quite compatible with use of the same storage plant for arbitrage.[8]

The implications of this may be significant: consider storage used for just one year of T&D deferral and then left in place for arbitrage plus ancillary services for ten years. Contrast that with storage deployed in location A, then moved to location B in year three and to location C in year five.

In the former example three storage plants are sold/used. In the latter example just one battery plant is sold/used. That is, the initial storage plant is used in location A then left in place for arbitrage and ancillary services, then two more storage plants are needed for T&D deferral at two additional locations (B and C), one in year three and one in year five.

Investigate Possible Air Quality Benefits from Distributed Storage

As noted above, energy storage may be one solution to air quality problems. Given the importance of air quality, it may be valuable to investigate prospects for distributed storage to reduce undesirable air emissions. Four facets to be investigated would include:

- Avoided T&D I^2R losses (net: on-peak – off-peak)
- Fewer central generation plant start-ups and avoided cycling/partial load operation of central fossil-fueled generation plants (and resulting inefficiency and increased emissions vis-à-vis full load operation)
- Use of "dump" energy (from coal, nuclear, and hydro) that would otherwise be wasted
- Reduced use of peaking generation that tends to be much less fuel efficient and that usually has much higher emissions (per kWh) than baseload generation.

Communication with Electric Utility Systems

Before distributed storage can be used to supplement the greater utility system, the necessary communication links will have to be in place. An initial investigation of this challenge would involve: 1) an evaluation of the status of relevant communication protocols, 2) a characterization of possible ways to enable market development in the near term while necessary standards and protocols are developed, and 3) a plan to develop or to influence development of standards and protocols.

Need for Distributed Storage Dispatch Logic

To address the need for commercial-grade logic for dispatching distributed storage for the arbitrage plus T&D deferral applications, research would include: a) survey of existing and emerging methodologies – hardware, software, and control systems, b) a characterization of what will be needed, and c) actions or programs needed to spur development.

Initial Characterization of Prospects for ESCOs as Marketmakers

It is assumed that, at least initially, only utilities will have the incentive and institutional means to use distributed storage for the arbitrage plus T&D deferral benefits. Eventually though, ESCOs may develop storage projects.

The goal of related research is to better understand prospects for ESCOs to serve as marketmakers for distributed storage. The potential role of ESCOs in market development for distributed storage (for the arbitrage plus T&D deferral applications) would be investigated and characterized. Possibilities to be investigated include use of load aggregation, shared savings, energy sales and purchase agreements, and capacity "contracts" with utilities.

Initial Characterization of Prospects for End-user-owned Distributed Storage

In some circumstances, electricity end-users may be in a better position to install distributed storage. Such a study would characterize the potential role of electricity end-users in the market for distributed storage used for the arbitrage plus T&D deferral applications. Possible mechanisms for end-users to justify use of storage might include direct energy and/or demand bill reduction, contracts with utilities or ESCOs, or I/C rates.

Appendix A–Secondary Benefits

A.1. Introduction

In addition to the two primary applications described in this study for DS, three additional (secondary) applications were considered:

1. Ancillary Services
2. Local Power Quality
3. Local Electric Service Reliability

One objective of the study was to evaluate prospects for energy storage systems to serve the primary applications and some or all of the secondary applications. If so, the resulting "supplemental benefits" would be added to benefits associated with the primary applications (energy buy-low-sell-high and T&D deferral).

A.2. Evaluation

Ancillary Services

Ancillary services involve electric resources used to optimize, stabilize, and otherwise "support" operation of the electricity grid. For example, some ancillary services involve maintaining grid voltage and frequency. Appendix G details the description of ancillary services.

The authors found that the *technical* requirements for energy storage equipment used for energy buy-low-sell-high and/or or used in lieu of T&D capacity are compatible with requirements for most ancillary services. This is consistent with the most recent Sandia National Laboratories report "Innovative Business Cases For Energy Storage in a Restructured Electricity Marketplace," SAND03-0362. Perhaps the one exception to this observation is that storage systems used for most ancillary services require a more rapid response time than systems used for buy-low-sell-high and for T&D capacity.

In addition to being technically compatible, buy-low-sell-high financial transactions are also compatible with those for ancillary services. Consider a situation where storage provides ancillary services with value higher than the price of electric energy. In that case, storage would be used for buy-low-sell-high transactions when not providing ancillary services. That is, owners schedule buy-low-sell-high transactions around ancillary services–related commitments.

For example, a storage unit can sell into a high-price energy market for a specific time period (say, a three- to four-hour afternoon system peak), dispatch for T&D load clipping during another time period, provide regulation or reactive supply (both ancillary services) during other time periods, etc., all within the same 24-hour period. However, it is important to note that there may not be enough time for the storage to recharge, hopefully with low priced energy, if it is to serve all of these applications.

However, despite the technological compatibility between storage used for T&D capacity and for ancillary services, *operationally* it is not possible to provide both T&D capacity and ancillary services simultaneously. Please see Appendix E for a detailed characterization.

Readers should also note that though storage can indeed provide ancillary services in a technical sense, the marketplace for ancillary services is just developing. Given that, the general state of transition in the utility industry, and given the lack of standardized definitions of, and contracts and payments for ancillary services, it is difficult to generalize related financial benefits.

Service Reliability and Power Quality

The two remaining secondary applications – improved power quality (PQ) and reliability–are very circumstance-specific and thus their compatibility with other applications cannot be generalized easily. However, in some cases they may indeed be additive with the primary applications. For example, storage used primarily to defer an upgrade could be located at the facility of a utility customer that requires especially high service reliability and/or power quality.

As with ancillary services, there is not a well defined "marketplace" for power quality or reliability "services." To the extent that markets do exist, they are driven by customer-specific criteria and rarely involve utility/end-user transactions.

A.3. Utility Comments about Supplemental Benefits

Based mostly on comments from Utility 1, storage located within the distribution system would indeed reduce the amount of capacity needed upstream to serve a given amount of customer load. If storage capacity was significant enough, responsible parties would need less capacity in the future.

I^2R losses, like fuel costs, are a "pass-through" to the energy customer. So, because these costs reductions are not reflected in the utility's bottom line there is no direct incentive to reduce the losses. However, to the extent that losses affect capacity needs, the utility does have an incentive to reduce the losses. Fortunately for DS, when utility circuits are heavily overloaded, incremental I^2R losses can have a significant effect on the load carrying capability of the circuit.

Regarding PQ and reliability–there is no way to quantify the value unless deals could be made with specific customers. The utility would be paid for the "service," establishing the "benefit." The service would be something like providing a power conditioner and/or a facility-wide UPS.

Though all supplemental benefits may actually accrue for improved PQ or reliability, or for reduced I^2R losses, whether DS receives credit for the benefits will depend heavily on who will get credit and/or blame for what. This is especially true in a monetary sense. Most utilities cannot and indeed are reluctant to ascribe a financial benefit to specific reduction in distribution capacity requirements, reduced I^2R losses (local), or for improved service reliability or power quality.

A.4. Secondary Benefits Conclusions

It is not practical to use storage for the primary applications and for ancillary services because ancillary services are likely to be required during the same times as T&D capacity is needed and when energy sales are most profitable. Though benefits associated with superior power quality and service reliability can be substantial (and can even be the primary driver for a decision to use storage) they cannot be generalized and are not likely to apply in all circumstances.

Therefore, supplemental financial benefits from secondary applications will not be included in the value proposition for this study.

Appendix B. Average Energy Buy-and-Sell Prices

The following charts, Figures B-1 and B-2, are presented to show details about energy purchases and sales for energy storage plants with storage durations ranging from one hour to ten hours, for storage plants with 70% and 90% round trip efficiencies. Bars represent average buy and average sell prices. The line plot indicates the average net benefit (per transaction) given average purchase and sale prices and storage efficiency.

On the top of each chart, for all storage plant durations (1 – 10), the number of annual transactions is shown. Multiplying the transactions by the average net benefit per transaction yields the total net benefit, for respective storage durations.

Note that the average energy purchase price, average "sell" price, and average net benefit (profit in the chart) all drop off as hours of storage discharge duration increase.

This information is provided for reference only. Average values are not helpful for decision-making; that requires estimates of total and marginal costs and benefits.

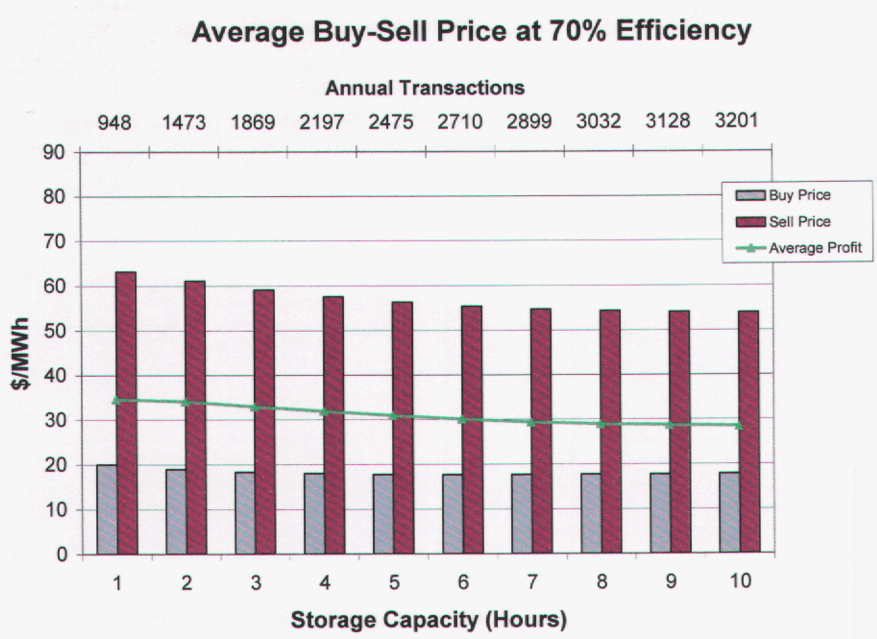

Figure B-1. Average Buy-Sell Prices at 70% Efficiency.

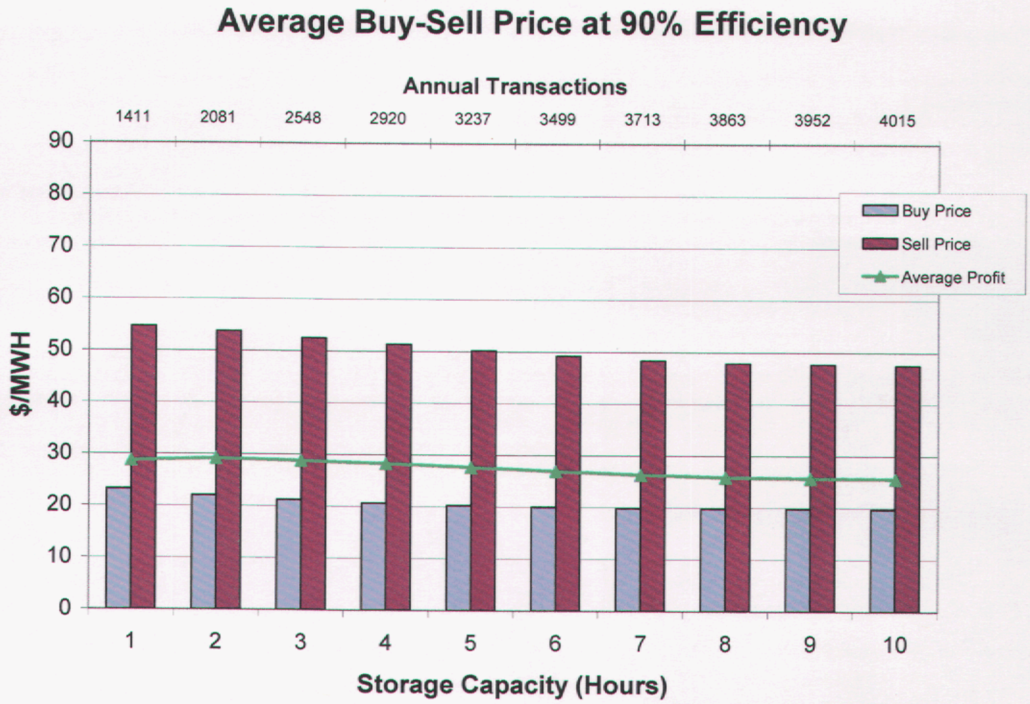

Figure B-2. Average Buy-Sell Price at 90% Efficiency.

Appendix C Arbitrage Algorithm

Introduction

The purpose of this algorithm is to estimate the annual financial benefits for energy price arbitrage using historic time series price data. Prices are presented in chronological order.

The logic optimizes hourly buy/sell (charge/discharge) transactions, based on several criteria including storage plant discharge duration, price for charging energy, "sell" price (that is known), storage efficiency, and storage variable maintenance cost.

Charging cost is defined as: $ buy-price/efficiency.

For example, if energy is available for $3/MWh to charge a 70% efficient storage plant, then charging cost is:

$3/MWh ÷ 0.7 = $4.3/MWh

The result of the exercise is to calculate the net financial benefit associated with all "profitable" transactions within a year. Profitable is defined as a transaction for which there is a net benefit. Net benefit is calculated as

$ price for energy discharged—$ price to buy energy/efficiency.

Note that this methodology uses historical hourly (average) price data. It reflects "perfect knowledge" about the future at any point in time.

Each transaction results in a storage discharge of exactly one hour. For example, if a plant is rated at 1 MW then for each transaction there is 1 MWh of energy discharged over exactly one hour. Implicit in the approach used is the assumption that the storage plant can be charged in one hour.

Methodology

The logic used for the dispatch algorithm is described below. Note that the description is for dispatch of a storage plant with a discharge duration of one hour. The logic for dispatching storage plants with more than one hour of discharge duration is described later in this Appendix.

Key Principle

Because the objective is to buy low and sell high, charging would occur only during hours that are local minima (price), and discharge would occur only during hours that are local maxima in the series. The minima occur at hours when the price is lower than the preceding and the following hours, and the maxima occurs when the price is higher than the preceding and following hours.

Step 1. Eliminate "Unusable" Hours

This step involves elimination of hours from the dataset for which a decision to charge or discharge would be suboptimal. Recall that charging occurs only during hours that are local minima and discharge occurs only during hours that are local maxima in the series. So, for a storage plant with a one-hour discharge duration, buying or selling during any hours between minima (charging) and between maxima (discharging) is not optimal. They therefore are deleted from the dataset.

Step 2. Algorithm

The objective is to maximize net benefits from buy-low-sell-high opportunities.

Charging/Buy Decision

The objective is to buy at the lowest possible price. For any "current" hour, the logic "looks ahead." It evaluates hours between the current minimum (the minimum containing the current hour) and the next minimum that is lower. Between those two minima, it locates the highest maximum price that exceeds the charging cost in the current hour, if any. That is, it determines whether the benefit for discharged energy at the respective future maximum in the series is greater than the current price. If there *is* a maximum price that exceeds the charging cost then the energy is purchased and stored. In other words, the "buy decision" is based on whether the energy can be sold at a later time for more than the net cost.

Discharge/Sell Decision

The objective is to discharge/sell to maximize net benefit. As with the charge/buy decision, for any current hour the logic looks ahead. It evaluates hours between the current maximum and the next maximum that is higher. Between those two maxima, the algorithm determines whether there is a minimum price at which the charging cost is less than the current hour's price. That is, it determines whether the charging cost at the respective future minimum in the series is less than the current price. If so, the decision to discharge/sell is made.

Annual Total

The net benefit for all discharge/sell transactions are summed to calculate the annual net benefits.

Storage Discharge Duration > One Hour

Analyzing storage plants with more than one hour of storage discharge duration requires one step like that described above for each additional hour. After each hour of storage discharge is processed, the hours (in the series) during which energy was purchased or discharged are removed from the price/cost table. As more hours of storage discharge duration are added to a storage plant, the net benefit for additional transactions diminishes.

Adjusting for Storage Charge Durations Less Than Discharge Durations

A modification is required to the algorithm to allow for a charge-to-discharge ratio greater than one (e.g., if it takes one hour to store enough energy to discharge the storage plant for two hours, the charge-to-discharge ratio is 1:2 or 0.5).

To process the first hour of storage, the logic is as described above (for a storage plant with one hour of storage with a charge to discharge ratio of 1); but instead of eliminating "buy" hours from consideration when first used, the respective buy hours are "tagged" with a 1 to designate the amount bought (in that hour). That way (for a charge to discharge ratio of 0.5), the algorithm can determine whether additional charging can occur during the respective hour.

Consider a two-hour storage plant. For a given minimum at which charging occurs, the first hour of storage is charged during ½ hour, and the minimum is tagged with a one. Then, when the algorithm seeks to charge the second storage hour, it knows that it can do so from the same minimum (hour) during which energy was stored for the plant's first storage hour. After that, the respective minimum is tagged with a 2, indicating that no additional charging can occur in that hour. Once the maximum possible storage has occurred during the respective minimum, it is eliminated from consideration, just like it was for a charge/discharge duration ratio of one.

After processing several hours of storage, because the algorithm eliminates more discharge hours than charge hours, it is possible that an hour during which charging occurred will suddenly be viewed as a local maximum and therefore a potential "sell" hour. To avoid this, the algorithm is not allowed to charge during an hour that is a local maximum.

Appendix D. Storage Discharge Duration Estimate -- Details

This appendix provides details about the methodology used to determine discharge duration for one case evaluated for this study. The first chart below shows actual loads for 150 days during 2000, escalated by one year's load growth. Evaluation of loads (leading to an estimate of the amount of storage needed) begins with the peak load day in the dataset. For this evaluation, the peak load day was August 8, 2000. The peak load that day was 42.2 MW.

It is assumed that the load *profile* for the historic peak load day is a good indication of the *profile* of a peak load day in the future. To that peak load, load growth is added to determine the amount of capacity (i.e., rated power output) and storage duration (hours of output at rated power) needed to meet load growth. This process is repeated for each year to be evaluated.

The charts (D-1, D-2, D-3, and D-4) below depict the effect of one year's load growth. For the first year evaluated, the load growth was 4% * 42.2 MW = 1.7 MW. Therefore, 1.7-MW "capacity" (in this case from storage) was needed to meet load growth for that year. (Note: in the chart, the load growth is labeled "Load > Ceiling", where "Ceiling" is the peak load in year 0.)

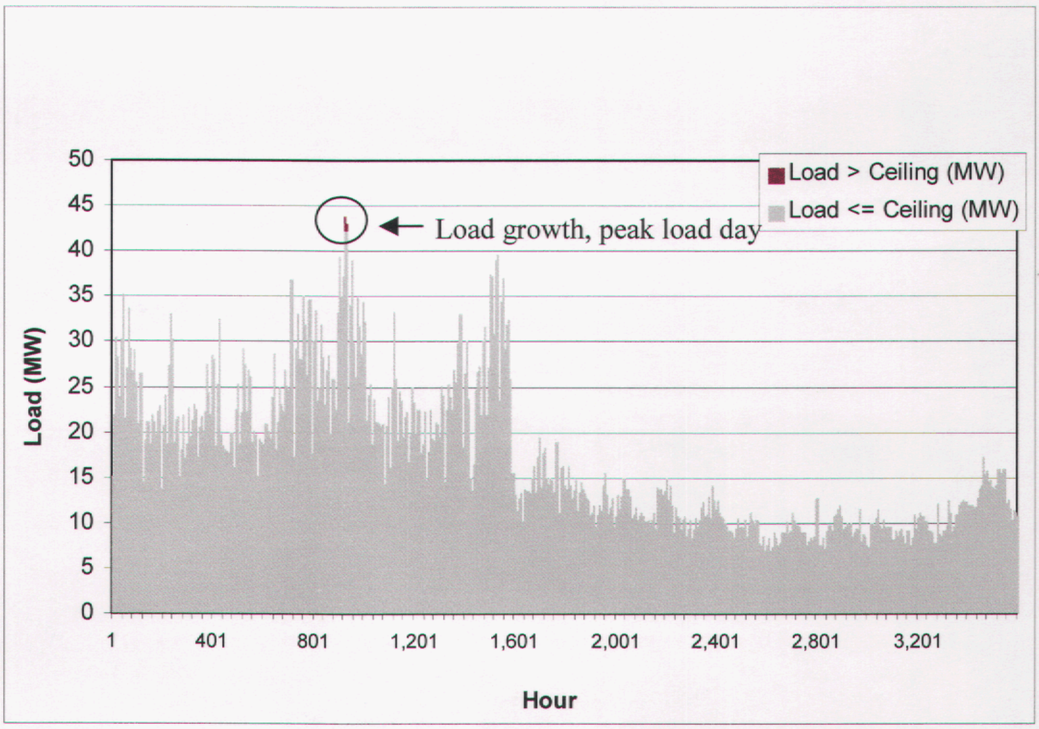

Figure D-1. Load Data, July 1, 2000, to November 21, 2000 (150 days), Plus One Year of Load Growth at 4.0%/yr.

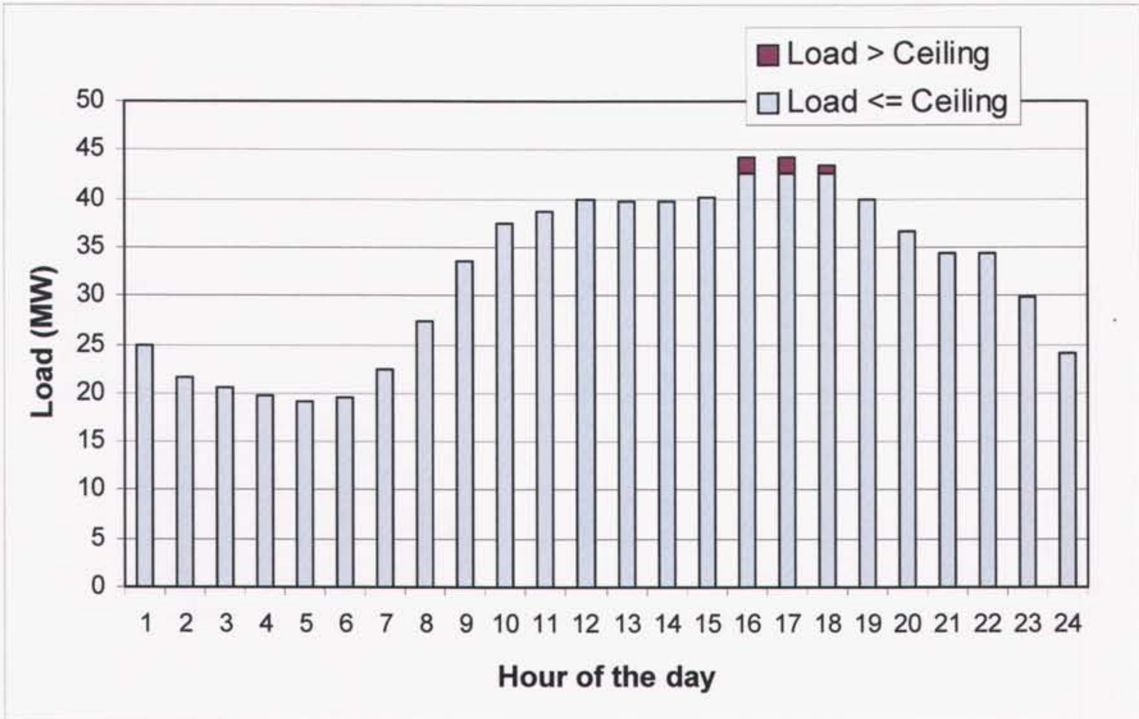

Figure D-2. Hourly Loads for August 8, 2000, Escalated at 4.0% for One Year.

Storage output capacity (MW) added to meet load growth matches load growth MW–for – MW. This is not the case for the duration of energy storage. As more years of load growth are served, the number of hours of storage required (per MW of peak capacity) to serve additional MWs of load depends on the "peakiness" of demand.

This effect is shown graphically by contrasting the chart just above showing effects from one year's load growth with the similar chart below showing load growth for *four* years. From those figures, for the first year of deferral the storage plant will need a discharge duration of two to three hours. To defer the capacity upgrade for the fourth year, the storage discharge duration must be about nine hours.

Eventually the number of hours of storage required to meet annual load growth becomes impractical. For the study, ten hours of storage was the maximum evaluated.

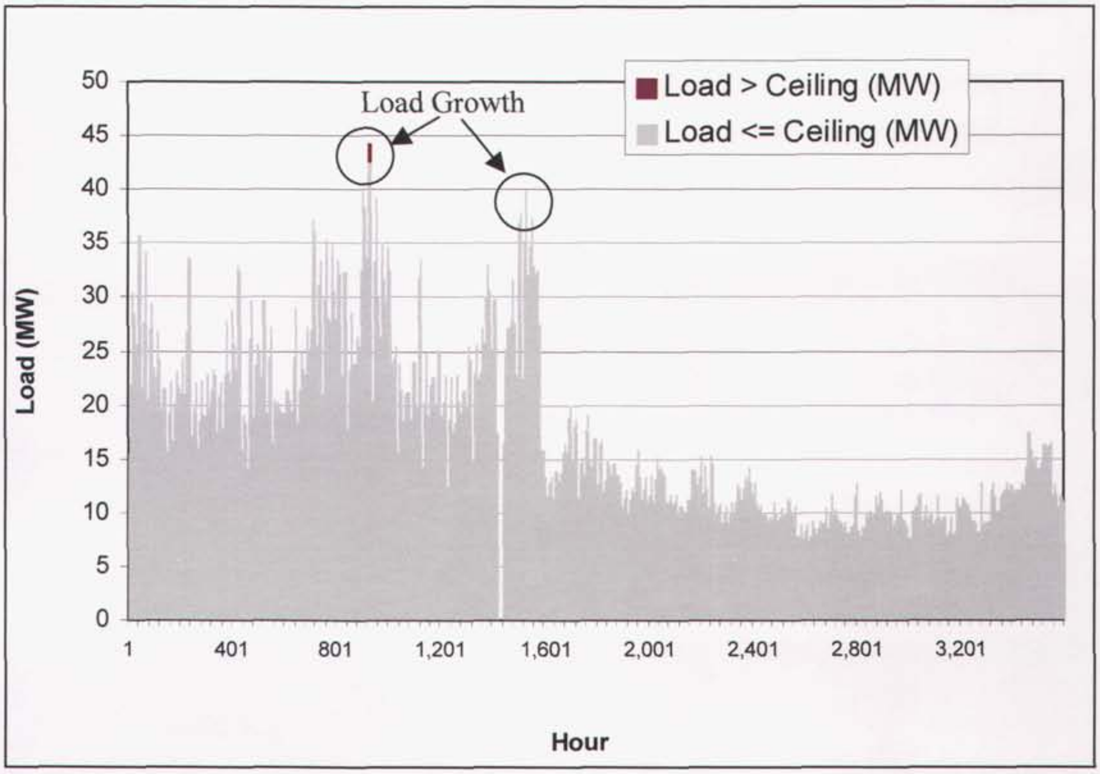

Figure D-3. Load Data, July 1, 2000, to November 21, 2000 (150 days), Plus Four Years of Load Growth at 4.0%/yr.

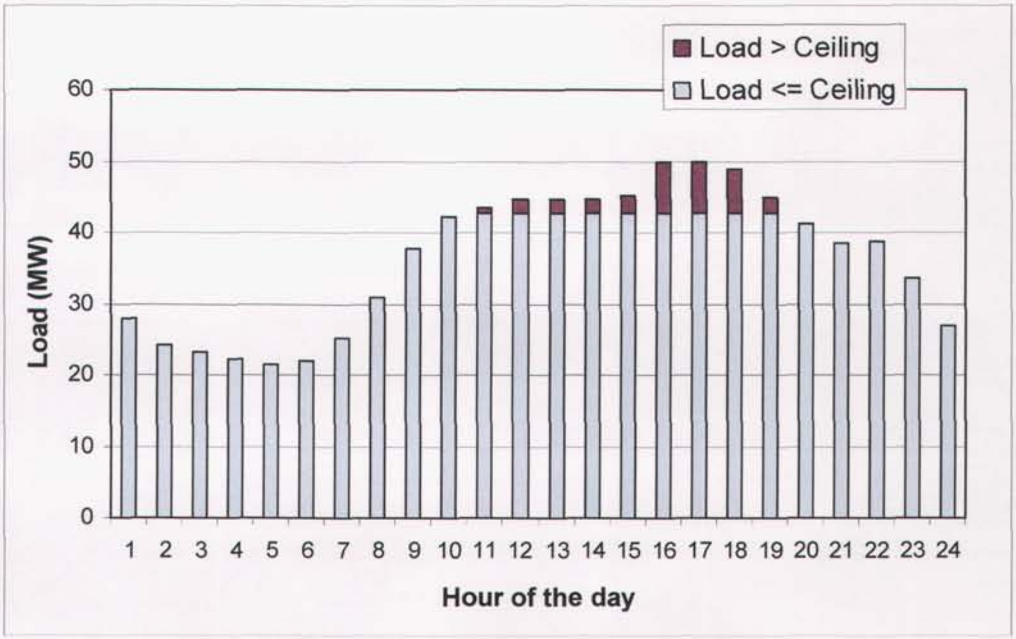

Figure D-4. Hourly Loads for August 8, 2000 (Tuesday), Escalated at 4.0% for Four Years.

Appendix E. T&D Deferral Benefits – Details

The following subsections show calculations used to estimate T&D deferral benefits for the five cases evaluated, four of which are specific real-life cases and one is a generic case. To estimate total benefits, these values are added to the energy price arbitrage benefits described in Section 2.2.

Case 1: Utility #1, Specific Upgrades

Case 1.a. 2002 Service Upgrade to Island

There are three specific upgrades with a combined cost of $10.6 million. They are: 1) 69 - kV service to island–$5.3 million, 2) new island substation–$3.8 million, and 3) 12.47 - kV Feeders–$1.5 million.

Item	Value	Note
Would have been deferred	$10.6 million	
Peak load growth 2002	2.1 MW	
Annual deferral benefit	$837,400	$10.6 million * .079 cost-of-capital
Deferral benefit from storage	$399 / kW	$837,400 / 2,100 kW load growth

For a plant that can provide 2.1 MW.

Case 1.b. 2006 VAR Support to Island

In 2006 there is a need for capacitors to provide VAR support to the island. By serving load growth in 2005 with a battery, the capacitor bank can be deferred.

Item	Value	Note
Cost for deferrable project	$1.2 million	
Escalate at 3% (2002 – 2006)	$1.35 million	(1+.03)^4 = 1.125
Annual deferral benefit	$106,650	$1.35 million * .079 cost-of-capital
Load 2005	73.9 MW	
Load growth 2005	2.1 MW	76 MW (load 2006) – 73.9 MW
Deferral benefit from storage	$51/kW	$195,000 / 2,600 kW

For a plant that can provide 2.1 MW for two hours.

Case 1.c. 2010 Upgrade Transmission to Island

Projected peak load in 2009 on the island is 82.4 MW. That is roughly equal to the maximum load carrying capacity of the equipment. An upgrade is needed in 2010.

Item	Value	Note
Cost for deferrable project	$1.925 million	
Escalate at 3% (2002 – 2010)	$2.47 million	(1+.03)^8 = 1.2667
Annual deferral benefit	$195,140	$2.47 million * .079 cost-of-capital
Load 2009	82.4 MW	
Load growth 2009	2.6 MW	85 MVA (load 2010) - 82.6 MW
Deferral benefit from storage	$75/kW	$195,000 / 2,600 kW

For a plant that can provide 2.6 MW for two hours.

Case 1.d. Upgrade Circuit

Use of storage located at or near the end of an overloaded circuit, to unload the circuit, so that only a portion of it must be upgraded.

Item	Value	Note
Cost for deferrable project	$1.3 million	per email July 15
Annual deferral benefit	$102,700	$1.3 million * .079 cost-of-capital
Load growth '03 – '05	1.5 MW	per email July 15
Load growth 2003	500 kW	1.5 MVA / 3 years
Deferral benefit from storage	$205/kW	$102,700 / 500 kW

For a plant that can provide 500 kW for two hours.

Case 2: Utility #2, "Generic" Hot Spot Upgrade Cost

The worksheet below shows calculations made to estimate the benefits for deferral for utility #2. The value of $35/kW-year of deferral value (per kW of nameplate rated capacity of utility equipment) is assumed to be indicative of high cost upgrades for which storage could be technically viable.

Based on the results shown, storage used to defer the upgrade by one year is worth over $900/kW of storage. Note the large investment "lump" required for the upgrade; in this case a 66% capacity addition is required. In the first year of that investment, only one 26^{th} of the entire capacity is needed.

Stated another way, a storage plant with a power output capacity of 1/26th that of the utility upgrade's nameplate rating can be used to defer the utility upgrade for one year, for a financial benefit of $923/kW.

Capacity Upgrade Deferral Benefit

Alternative	Storage
Capacity Existing (kVA)	42,000
Capacity Addition (kVA)	27,700
Upgrade Factor (kVA Added / kVA Existing)	.66
Addition Life (Years)	20.51
Demand Growth Rate (%/year)	2.5%
Load Growth, Year 1 (kVA)	1,050
Storage "Oversizing Factor" (%)	0.0%
Storage Capacity Needed to Meet Load Growth, Year 1 (kVA)	1,050
Fixed Charge Rate	.15
Single Year Deferral Benefit, for Distribution Upgrade ($/kVA, Year 1)	35
Plant Installed Cost	233.3
Ratio: Upgrade Capacity to Storage Capacity	26.4
Single Year Deferral Benefit for Storage Used to Meet Load Growth, Year 1 ($kVA) * Calculated as *Single Year Deferral Benefit for Storage times Upgrade Capacity To Storage Capacity Ratio*	923*

Appendix F. Applications Attributes Matrix

The application attributes matrix shown below in Table F-1 was used to summarize the technical requirements of the primary and secondary applications described in Section 2. It was also used to evaluate the compatibility between the various applications. The criteria listed are described or defined in Section 2. The secondary applications are described in more detail in Appendix A.

Table F-1. Applications Attributes Matrix

			Reliability			Response		Power Quality					Control			Form Factor		
Application	Voltage (kV)	# of events per year	Scheduled Outage Rate	Unscheduled Outage Rate	Performance Gaurantee (importance)	Startup Delay (milliseconds)	Ramp Rate (%nominal power /millisecond)	Voltage Surges/Sags	Frequency Stability (+/- cycles/sec.)	Minimum Power Factor	Controllable Power Factor Range (max lag/lead)	Harmonics (THD)	"Flexible" Communications* (importance)	Special Controls	Self-Diagnostics (importance)	Floor Space, amount required (importance)	Portability (importance)	Modularity (importance)
Arbitrage	.5 - 30	100-1,000	<10%	<5%	Low	hours	<1%	+/-50%	.5	.85	n/a	IEEE 519	Moderate	Buy-low, Sell-high	Low	Low	Low	Low
Transmission Facility Deferrals	100 - 500	1-20	<50%	<.1%	High	minutes	25% A.	+/-70%	.2	.90	.9 - .7		High	Rapid response electrical	High	Moderate	Moderate	Moderate
Distribution Facility Deferrals	5 - 50	1-20	<50%	<.1%	High	minutes	1% B.	+/-70%	.2	.90	.85 - .7		High	Rapid response electrical	Moderate	Moderate	High	High
Ancillary Services																		
1. System Control	100 - 500	n/a	<10%	<.1%	High	msecs	25% A.	+/-50%	.5	.85	.9 - .7		High	Rapid response electrical	High	High	Low	Moderate
2. Reactive/Voltage Control	100 - 500	thousands	<10%	<.1%	High	msecs	25% A.	+/-50%	.5	.85	.9 - .7		High	Rapid response electrical	Moderate	Moderate	Low	Moderate
3. Regulation	100 - 500	thousands	<10%	<.1%	High	msecs	25% A.	+/-50%	.5	.85	.9 - .7		High	Rapid response electrical	High	High	Low	Moderate
4. Spinning Reserve	100 - 500	0 - 20	<10%	<1%	Moderate	1 - 10 sec.	1% B.	+/-50%	.5	.85	.9 - n/a		High		Moderate	Low	Low	Moderate
5. Supplemental Reserve	100 - 500	0 - 5	<10%	<1%	High	1 - 10 min.	< 1%	+/-50%	.5	.85	.9 - n/a		High		Moderate	Low	Low	Moderate
6. Load Following	100 - 500	1 - 50	<10%	<.1%	Moderate	5 min.	2.5% A.	+/-50%	.5	.85	.9 - n/a		High		Moderate	Low	Low	Moderate
7. Backup Supply	100 - 500	0 - 2	<10%	<1%	High	1 hour	< 1%	+/-50%	.5	.85	.9 - n/a		High		Moderate	Low	Low	Moderate
8. Dynamic Scheduling	100 - 500	>1000	<10%	<.1%	High	msecs	25% A.	+/-50%	.5	.85	.9 - n/a		High		Moderate	Low	Low	Moderate
9. Black Start	100 - 500	0 - 1	<10%	<1%	High	30 min. - 2 hrs	< 1%.	n/a	n/a	n/a	.9 - n/a		High		Low	Low	Low	Moderate
10. Network Stability	100 - 500	>1000	<10%	<1%	High	msecs	25% A.	+/-70%	.2	.90	.9 - n/a		High	Rapid response electrical	High	Low	Low	Moderate
11. Congestion Management	100 - 500	1 - 50	<10%	<.1%	High	1 hour	1% B.	+/-70%	.2	.90	.9 - n/a		High		High	Low	Low	Moderate
12. Real Power Loss Replacement	100 - 500	1 - 10	<10%	<.1%	High	1 hour	25% A.	+/-70%	.2	.90	.9 - n/a		High		Moderate	Low	Low	Moderate
Local Reliability	1 - 10	1 - 5	<10%	<.1%	High	msecs	2.5% A.	+/-70%	.2	.85	.85 - n/a		High			Moderate	High	Moderate
Local Power Quality	1 - 10	>1000	<10%	<.1%	High	msecs	2.5% A.	+/-70%	.2	.85	.85 - .7		High			Moderate	High	Moderate

msec=milliseconds
A. 1/4 cycle--1/60 * .25 = .00417 seconds = 4.2 msecs\ 25% ramp rate
B. 5 cycles—5/60 = 0833 seconds = 83.3 msecs. 1/83.3 = 1.2%/msec
* Cap communication via common protocols
** Systems assumed to include charge controls

Appendix G. Ancillary Services

G.1. Overview

The primary function of the electric power system is to supply electric energy from generators and deliver it to customers via the transmission and distribution systems. Ancillary services are defined by the Federal Energy Regulatory Commission (FERC) as those services necessary to support the delivery of electricity from seller to purchaser while maintaining the integrity and reliability of the interconnected transmission system ("the network").

The objective of this analysis is to evaluate the potential of energy storage technologies to serve markets for **ancillary services**, in addition to the two primary applications studied.

G.2. Definitions

Table G-1 is a list of the most common ancillary services and their generally accepted definitions. FERC's Order 888 includes a *pro forma* tariff with provisions for six ancillary services (items 1 – 6). The first two, System Control and Reactive Supply & Voltage Control, are mandatory, i.e., under FERC rules transmission providers (transmission system operators, or TSOs) must supply these functions and customers must take them from the transmission providers.

Ancillary services 4 through 6 are seen by FERC as essential services that must be offered by the TSO, but that customers are not required to take; that is, these services could be acquired from the TSO, through competitive markets, or self-supplied by customers.

In addition, the National Electric Reliability Council's (NERC) Interconnected Operations Services Working Group has identified six ancillary services that it considers essential to the operation of bulk power systems (items 7 – 12). FERC does not require transmission providers to offer these six ancillary services.

Finally, Congestion Management (item 13) has been mentioned in recent years as a possible ancillary service, and is noted here in the interest of inclusiveness.

Table G-1. List of Ancillary Services and Their Common Definitions

1. System Control	Scheduling generation and transactions ahead of time, and controlling some generation in real time to maintain generation/load balance.
2. Reactive Supply & Voltage Control	The generation or absorption of reactive power from/to generators to maintain transmission system voltages within required ranges.
3. Regulation	Minute-by-minute generation/load balance within a control area to meet NERC standards.
4. Spinning Reserve	Generation capacity that is on-line but unloaded and that can respond within 10 minutes to compensate for generation or transmission outages. "Frequency-responsive" spinning reserve responds within 10 seconds to maintain system frequency.
5. Supplemental Reserve	Generation capacity that may be off-line, or curtailable load, that can respond within 10 minutes to compensate for generation or transmission outages.
6. Energy Imbalance	Correcting for mismatches between actual and scheduled transactions on an hourly basis.
7. Load Following	Generation dispatched to meet hour-to-hour and daily load variations.
8. Backup Supply	Generation available within an hour, for backing up reserves or for commercial transactions.
9. Real Power Loss Replacement	Generation that compensates for real power losses in the T&D system.
10. Dynamic Scheduling	Real-time control to electronically transfer either a generator's output or a customer's load from one control area to another.
11. Black Start	Ability to energize part of a grid without outside assistance after a blackout occurs.
12. Network Stability	Real-time response to system disturbances to maintain system stability or security.
13. Congestion Management	Dispatch of generation to relieve loading on a congested transmission line or path.

[Refs. 9 & 10]

G.3. Analysis

System Control: By definition, this is a scheduling and control function, not a generation-based service; therefore it is not relevant to storage systems.

Reactive Supply & Voltage Control: Maintaining correct system voltage is seen as being most efficiently accomplished through a combination of interconnection and operating requirements between the entity providing centralized system control, such as a transmission provider, TSO or independent system operator (ISO), and the generators. The system controller may also have other equipment under its direct control, such as capacitors, synchronous condensers, etc. Voltage problems are almost always local in nature, and the TSO is usually the only entity having sufficient information and control of resources available to make the appropriate corrective actions. Region- or system-wide voltage problems may be indicative of larger problems such as multiple line outages, but in any case must be dealt with on a system-wide basis.

FERC has been skeptical that a sufficient number of independent resources would be available in most localized situations for there to be a viable competitive market for reactive supply, and for this reason has preferred that reactive supply remain a regulated commodity. Still, assuming that a competitive market develops, it is possible that storage could bid its supply in response to a call for reactive resources by an ISO, especially if shortages should develop. [10]

As an ancillary service, reactive supply is potentially compatible with energy arbitrage in the sense that energy bought at times of low prices could be dispatched as reactive power if the price is right, just as for any other high-value use. It is also potentially compatible with T&D deferral exclusive of the time periods reserved for that application. The further advantage in this case is that the only real power expended is due to efficiency losses in the storage system itself, and possibly the additional T&D losses incurred in moving the reactive power through the T&D network. The result is that the storage unit will be only partially discharged after providing reactive supply, shortening the normal recharge interval before the next transaction.

Regulation: This service is defined as a "plus-minus" dispatch around a given operating point, such that total energy dispatched will equal total energy absorbed over the time period contracted, neglecting efficiency losses. Regulation via storage is technically compatible with both energy arbitrage and T&D deferral, though storage cannot provide these services simultaneously.

Spinning Reserve: The generating unit must be on-line but unloaded, and capable of responding to operator commands to full power in 10 minutes. Though spinning reserve is compatible technically with buy-low-sell-high and T&D deferral applications, storage cannot provide spinning reserve at the same time that it provides T&D capacity or energy arbitrage.

Supplemental Reserve: Similar to spinning reserve, except the unit may be off-line and must capable of connecting to the grid at full power in 10 minutes. Storage cannot provide both T&D deferral and supplemental reserve at the same time.

Energy Imbalance: The storage unit may be called upon either to supply a net amount of power, or to absorb a net amount of power, due to imbalances in the market. Obviously, the storage unit can only absorb power if it is discharged, and supply power if it is charged. Therefore, though this ancillary service is technically compatible with both the T&D deferral and the energy buy-low-sell-high applications, operationally they are not compatible.

Load Following: Load following units discharge power to "follow" area or system load as it varies during the day. Load following is technically compatible with both energy arbitrage and T&D deferral, though storage cannot provide load following at the same time that it is used for the primary applications.

Backup Supply: This is the third level of reserve, after spinning and supplemental reserves. Storage serving this application must be able to be on-line within one hour. This ancillary service is compatible with the primary applications though it cannot be provided at the same time as energy arbitrage or T&D capacity.

Real Power Loss Replacement: Losses are nonlinear in nature and are difficult to compute in real time, making it correspondingly difficult to assign costs to particular market participants. Still, various arrangements under which losses could be accounted for in a market-based system have been proposed. The simplest approach may be to include Loss Replacement under the Regulation or Energy Imbalance functions rather than to account for it separately. This service is compatible with energy arbitrage, and possibly compatible with T&D deferral: by dispatching to clip system peaks, line losses will likely be reduced in the short term. However, in the long term, as average line loadings increase over time, line losses will increase. [1]

Dynamic Scheduling: This is a System Control function and hence not relevant for storage.

Black Start: Similar to backup supply, with the added condition that the unit must power itself up with no help from the grid, which most storage technologies should be capable of. However, in order to qualify as a black-start-capable unit, the storage system must be fully charged and kept in reserve, since it is not possible to predict exactly when a contingency will cause a blackout. Because of the need to ensure that the unit is charged when needed, black start capability is not compatible with any other service or application.

Network Stability: The dominant factor in damping of system oscillations is the speed of the phased response from the inverter. These power swings can occur simultaneously with other discharge modes by utilizing the short-term overload capability of the inverter system. The plus-and-minus dispatch of the unit during stabilizing operation results in the net power expended from the storage unit being relatively small, consisting of the damping power absorbed by the grid plus additional T&D system losses and storage system efficiency losses. Therefore, this service should be fully compatible with all other ancillary services, as well as with energy arbitrage and T&D deferral applications, without constraints, and even during charging periods.

Congestion Management: Though this is not generally considered to be an ancillary service on the same basis as the ones described above, congestion management is an emerging need within the utility industry that is akin to ancillary services. The need for congestion management seems likely to increase as transmission corridors become overloaded during peak demand periods.

Storage used for congestion management must be in the proper location on the system in order to achieve congestion relief (i.e., downstream from constrained areas). As with reactive supply, the lack of sufficient competitive resources in specific geographical areas may lead FERC and state regulators to discourage the development of competitive markets for this service. However, assuming it is allowed, this service would be compatible with both energy arbitrage and T&D deferral, with the caveats previously stated.

The matrix shown in Table G-2 presents the above results in tabular form.

G.4. Compatibility between Primary Applications and Ancillary Services, Summary Conclusions

General Considerations

Generally, if a storage unit is performing an ancillary service, it cannot simultaneously perform any other ancillary service or application. It is possible, though, to split the operation of the storage to accommodate different applications or services during different time intervals. The storage system can dispatch its stored energy as real power (kW or MW), or as reactive power (kVAR or MVAR), which can be independent of each other.

Compatibility between Energy Arbitrage and Ancillary Services Applications

For evaluating the compatibility of an ancillary service with energy arbitrage, it is assumed that the operator of the storage unit has full real-time knowledge of the markets and their respective price signals, and will manage the operation of the unit so as to maximize its economics. In general, the storage operator will dispatch those services or applications with the greatest monetary return (highest price signals), which may change on an hourly basis (but keeping in mind only one service or application can be served at a time). In some cases, ancillary services could be served while the unit is being charged or is only partially charged.

Compatibility between T&D Deferral and Ancillary Services Applications

For transmission and distribution deferral, it is assumed that the storage unit is contracted to dispatch during specified time periods (e.g., 2:00 to 6:00 p.m. on summer weekdays) to clip T&D loading peaks; generally, no other services or applications can be served during those contracted times. Outside the contracted times, the storage unit is free to serve whatever services it can, subject to the charging constraints of the T&D deferral requirements.

Table G-2 List of Ancillary Services and Their Characteristics

Name	Service Duration	Dispatch Frequency	Mills/kWh[1]	$/kW-year[2]	Client[4]	Benefits/Issues	Storage "Business" Compatibility with: Arbitrage	T&D Deferral
System Control	Continuous	Daily	N/A	N/A	TSO	A control function FERC mandates, and that TSO must supply; not relevant to storage.	N/A	N/A
Reactive Supply/Voltage Regulation	Continuous	Daily	0.4		TSO/DSO	Ditto above. Uncertain whether competitive markets for this service will be feasible.	Yes	Yes[3]
Regulation	Continuous	Daily		30.0 – 290.0	TSO	Normally contracted for a ± MW, minute to minute basis: real power averages ~ 0 over time.	Yes	Yes[3]
Spinning Reserve	10 min.	20 per year (est.)		2.0 – 5.0	TSO	Must respond within 10 minutes	Yes	Yes[3]
Supplemental Reserve	30 min.	10 per year (est.)		2.0 – 5.0	TSO	Must respond within 10 minutes	Yes	Yes[3]
Energy Imbalance	Continuous	Daily	0.7		TSO	Must respond to signals on an hourly basis	Yes	Yes[3]
Load Following	Continuous	Daily	0.5		TSO/DSO	Must respond to signals on an hourly and daily basis	Yes	Yes[3]
Backup Supply	1 to 2 hrs	3 per year (est.)		2.0 – 5.0	TSO	Must respond within 1 hour	Yes	Yes[3]
Loss Reduction	Continuous	Daily	1.3		TSO/DSO	Deferring T&D using any distributed resource may lead to higher average line loadings, resulting in higher losses	Yes	Yes[3]
Dynamic Scheduling	Continuous	Daily			TSO	Essentially a control function; not relevant to storage	N/A	N/A
Black Start	30 min. to 8 hrs	2 per year (est.)			TSO/DSO	Storage unit must be fully charged to be able to qualify	No	No
Network Stability	15 sec. – 1 min.	Daily			TSO	Fully compatible with all other ancillary services and applications	Yes	Yes
Congestion Management	1 to 8 hours	During local peak loading periods			TSO	Very location-specific; not certain competitive markets will exist or be allowed.	Yes	Yes[3]

Notes: 1 Hirst, E., and Kirby, B., Oak Ridge National Laboratory: Ancillary Service Costs for 12 U.S. Electric Utilities[9]

2 Taylor, R., Hoagland, J., Bradshaw, D.: Energy Storage for Ancillary Services, EESAT 2002[3]

3 Caveat: Care must be taken to ensure that operation for ancillary services does not negatively impact the ability of the storage unit to operate for T&D deferral.

4 TSO = Transmission System Operator; DSO = Distribution System Operator

Appendix H. Depth of Discharge and Residency

H.1. Depth of Discharge

Figures H-1 and H-2 show the number of times that storage reaches a given discharge depth during one full year of operation for the arbitrage application. The two charts are for 70% and for 90% efficient storage plants, respectively, with discharge durations ranging from one hour to ten hours.

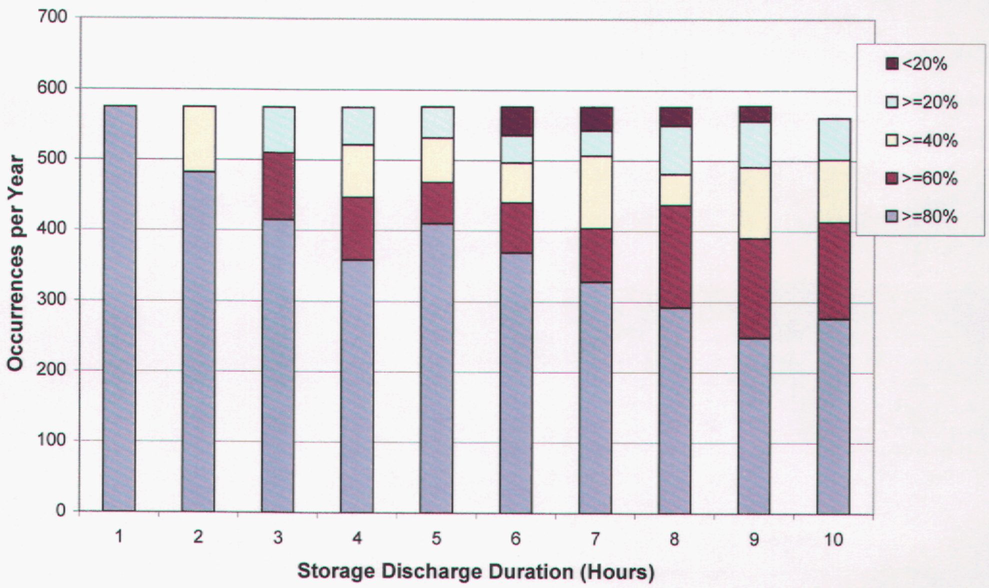

Figure H-1. Depth of Discharge Frequency for 70% Efficient Storage Plant.

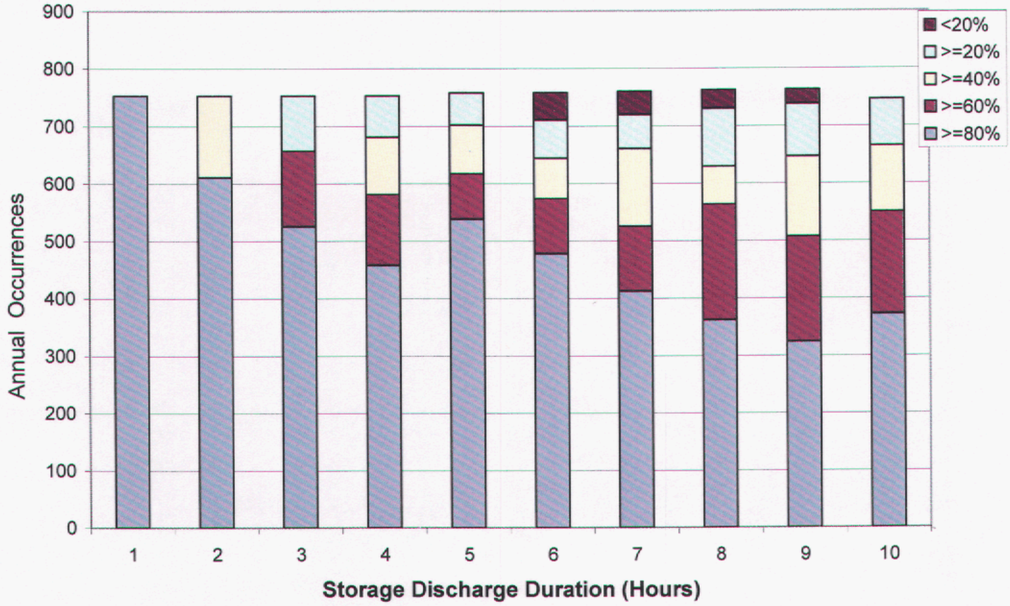

Figure H-2. Depth of Discharge Frequency for 90% Efficient Storage Plant.

H.2. Residence Time at Various Depth of Discharge Levels

Figures H-3 and H-4 show the amount of time that storage remains at a given level of discharge. Charts are for 70% and for 90% efficient storage systems. Life and maintenance costs for some storage technologies are affected by this condition. For each bar, the total number of hours is 8,760.

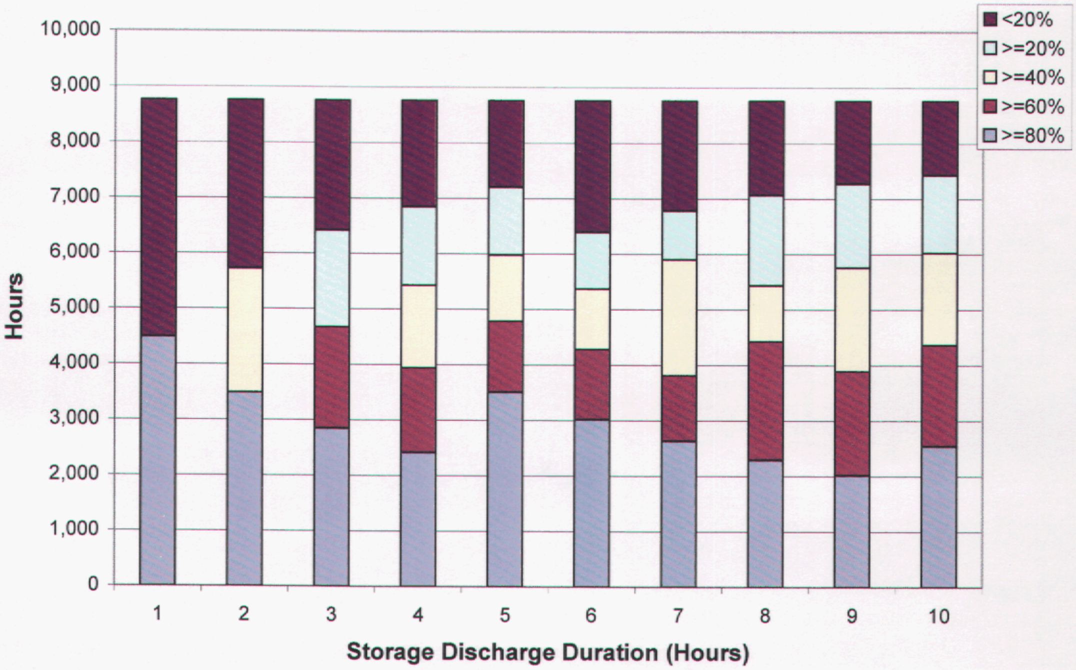

Figure H-3. Storage Residency for 70% Efficient Storage Plant.

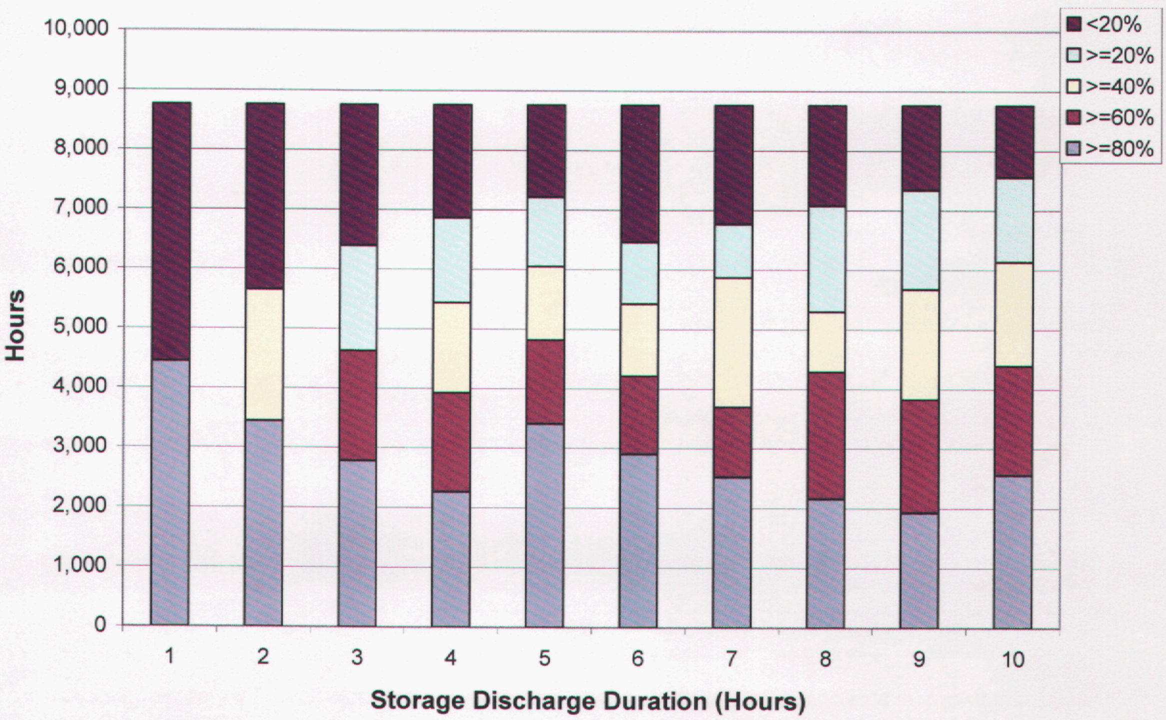

Figure H-4. Storage Residency for 90% Efficient Storage Plant.

Appendix I. Vendor Questionnaire

High Value-Added Energy Storage Applications Vendor Questionnaire

July 22nd, 2002

1 In the past, has your company considered energy arbitrage and T&D deferral as market opportunities for your storage products?

1.a If so, how would you describe your prior conclusions about the economic benefits and opportunities of this potential market?

2 Using the benefits and technical requirements identified in the economic analysis; do you believe that your company could provide a storage product that is consistent with the performance requirements shown?

2.a If not, please describe what advances would be required to allow you to meet these performance requirements.

3 Considering the life-cycle benefits estimated in this study as a target (indifference) life-cycle cost for storage, could your company provide a storage product whose cost that is at or below the benefits?

3.a Could you share what advances would be required to allow you to meet the indifference cost requirements?

3.b Would you be willing to specify a specific price point for your companies product? If so, please separate out the initial capital cost and likely operational and maintenance costs.

4 Considering your answers to 2 and 3, does this combined benefits opportunity look feasible and economically viable for you to consider in your business plans?

4.a A list of market challenges has been identified in this study. Please rank the challenges shown below. Please provide additional perspective on each. Please add any challenges which you believe to be absent from the list. (Ranking should be on a basis of Difficult, Somewhat Difficult, or Easy to overcome the challenges).

Technology cost and performance (D, S, E)

Barriers to economically efficient "risk and reward sharing" (D, S, E)

Interconnection requirements (D, S, E)

Permitting and siting (D, S, E)

Safety (D, S, E)

Demonstrated viability (D, S, E)

Unfamiliarity on the part of the user (D, S, E)

Unknown risk profiles (D, S, E)

5 A market vision will be written for this study. Would you please comment on the market vision you have for the storage applications identified. In your market vision, please identify market potential, timeframes to realizing such a market, and whom you see as likely owners of the storage technology (utilities, third party energy service companies, end user customers).

6 What additional information or analysis is needed to either firm up the benefits or to validate them further, such that your market/business plan would indeed be modified to reflect a commitment to these markets?

7 With the applications and benefits identified in the economic analysis, what steps should be taken next to enhance your ability in creating and realizing these markets? In your answer please consider the role of state and local regulators, utility financial and technical decision-makers, and the role of the federal government.

8 Would you be willing to consider involvement and participation in related future work with the Department of Energy?

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Distribution

Mr. Gerald W. Braun
14801 Braemar Crescent Way
Darnestown, MD 20878

Mr. Per Danfors
1029 W. Zermatt Dr. #8
Midway, UT 84049

Mr. Brad Johnson
2122 Natahoa Court
Falls Church, VA 22043

Dr. Nick Magnani
2494 Windmill Point Rd.
White Stone, VA 22578

Mr. Bob Weaver
12327 Dry Creek Road
Auburn, CA 95602-9339

Mr. Herbert Hayden
Arizona Public Service
400 N 5th Street
P.O. Box 53999, MS8931
Phoenix, AZ 85004

Mr. Hans Weinrich
ABB Power T&D Co., Inc.
1460 Livingston Ave.
P.O. Box 6005
North Brunswick, NJ 08902-6005

Mr. Warren Ziegler
Acumentrics Corporation
20 Southwest Park
Westwood, MA 02090

Dr. William V. Hassenzahl
Advanced Energy Analysis
1020 Rose Avenue
Piedmont, CA 94611

Mr. David Nichols
AEP
4001 Bixby Road
Groveport, OH 43125

Mr. Ali Nourai
AEP
1 Riverside Plaza
20th Floor
Columbus, OH 43215

Dr. Robert O. Bartlett
AFS Trinity Power Corporation
7617 Irongate Lane
Frederick, MD 21702

Mr. Donald A. Bender
AFS Trinity Power Corporation
6724D Preston Avenue
Livermore, CA 94551

Mr. Paul Grems Duncan
Airak, Inc.
9058 Euclid Avenue
Manassas, VA 20110-5308

Mr. Tim Mack
Airak, Inc.
9058 Euclid Ave.
Manassas, VA 20110

Mr. Dennis Meiners
Alaska Energy Authority
813 West Northern Lights Boulevard
Anchorage, AK 99503

Mr. Peter Crimp
Alaska Energy Authority/AIDEA
813 West Northern Lights Boulevard
Anchorage, AK 99503

Mr. David Lockard
Alaska Energy Authority/AIDEA
813 West Northern Lights Blvd.
Anchorage, AK 99503

Mr. Burkhard Römhild
ALSTOM Power, Inc.
2800 Waterford Lake Drive
Midlothian, VA 23112-3981

Dr. Christian Sasse
ALSTOM Research & Technology Centre
P.O. Box 30
Lichfield Road
Stafford, ST17 4LN
UNITED KINGDOM

Mr. Meera Kohler
Anchorage Municipal Light & Power
1200 East 1st Avenue
Anchorage, AK 99501

Mr. Richard Baxter
Ardour Capital
4 Menotomy Rd.
Suite 9
Arlington, MA 02476

Mr. Ira D. Bloom
Argonne National Laboratories
9700 South Cass Avenue CTD
Bldg. 205
Argonne, IL 60439

Mr. Christian St-Pierre
ARGO-TECH Productions, Inc.
Subsidiary of Hydro-Quebec
1580 de Coulomb
Boucherville, QC J4B 7Z7
CANADA

Mr. Ray Hobbs
Arizona Public Service
400 North Fifth Street
P.O. Box 5399, MS8931
Phoenix, AZ 85072-3999

Mr. Robert L. Hammond
Arizona State University EAST
1500 E. University Drive
Tempe, AZ 85281

Mr. Violaine Dorval
Avestor
1560 de Coulomb
Boucherville, QC J4B 7Z7
CANADA

Mr. William Capp
Beacon Power Corp.
234 Ballardvale Street
Wilmington, MA 01887

Mr. Matthew L. Lazarewicz
Beacon Power Corp.
234 Ballardvale Street
Wilmington, MA 01887

Mr. Michael L. Bergey
Bergey Windpower
2001 Priestley Avenue
Norman, OK 73069

Mr. Chris Marnay
Berkley National Laboratory
MS 90-4000 1 Cyclotron Rd.
Berkeley, CA 94720

Mr. Klaus Kraemer
Berlinger Kraft und Licht (BEWAG)
Bewag AG Energy Planning &Trading
Berlin, D-12432
GERMANY

Mr. Gerry Woolf
BEST Magazine
17 Westmeston Ave.
Rottingdean, East Sussex BN2 8AL
UNITED KINGDOM

Mr. Larry Stoddard
Black & Veatch
11401 Lamar Avenue
Overland Park, KS 66214

Mr. Charles Koontz
Black Oak Capital, LLC
P.O. Box 82073
Columbus, OH 43202

Dr. Michael Strasik, Ph.D.
Boeing Phantom Works
P.O. Box 3707
MS 7J-93
Seattle, WA 98124

Mr. Michael Hoffman
Bonneville Power Administration
P.O. Box 3621
Portland, OR 97208-3621

Mr. Roy Forey
British Embassy
3100 Massachusetts Avenue, NW
Washington, DC 20008-3600

Mr. Septimus van der Linden
Brulin Associates, L.L.C.
14418 Old Bond Street
Chesterfield, VA 23832

Dr. Sudhan S. Misra
C&D Technologies
1400 Union Meeting Road
Blue Bell, PA 19422-0858

Mr. Pramod P. Kulkarni
California Energy Commission
1516 9th Street
MS #43
Sacramento, CA 95758

Mr. John Cooley
Chugach Elec. Association, Inc.
5601 Minnesota Drive
P.O. Box 196300
Anchorage, AK 99519-6300

Mr. Tom Lovas
Chugach Elec. Association, Inc.
5601 Minnesota Dr.
P.O. Box 196300
Anchorage, AK 99519-6300

Mr. Stephen J. Steffel
Conectiv
Mail Stop Code 79NC58
P.O. Box 9239
Newark, DE 19714-9239

Mr. Victor E. Udo
Conectiv
401 Eagle Run Road
P.O. Box 9239
Newark, DE 19714

Mr. Michael A. Lankford
Detroit Edison
15600 19 Mile Road
Clinton Township, MI 48038

Mr. William Erdman
Distributed Utility Associates
114 Lucille Way
Orinda, CA 94563

Mr. James Eyer
Distributed Utility Associates
1062 Concannon Boulevard
Livermore, CA 94550

Dr. Susan Horgan
Distributed Utility Associates
1062 Concannon Boulevard
Livermore, CA 94550

Mr. Murray W. Davis
DTE Energy
37849 Interchange Dr.
Farmington Hills, MI 48335

Mr. Steven G. Whisenant
Duke Power Company
MC: EC04J 26 South Church St.
P.O. Box 1006
Charlotte, NC 28201

Mr. Dan Greenberg
E Source
3333 Walnut St.
Boulder, CO 80301-2515

Dr. Alan Collinson
EA Technology
Capenhurst, Chester CH1 6ES
UNITED KINGDOM

Mr. Jim DeGruson
Eagle-Picher Industries, Inc.
C & Porter Street
Joplin, MO 64802

Prof. Alfred Rufer
Ecole Polytechnique Federale de Lausanne
(EPFL)
LEI-STI-EPFL
Lausanne, CH1015
SWITZERLAND

Mr. K.M. Abraham
E-KEM Sciences
P.O. Box 920401
Needham, MA 2492

Mr. Kateri Callahan
Electric Drive Transporation Association
701 Pennsylvania Avenue NW
3rd Floor - East Building
Washington, DC 20004

Mr. Mark Skowronski
Electric Power Group
201 South Lake Avenue, Suite 400
Pasadena, CA 91101

Mr. Steve Chapel
Electric Power Research Institute
P.O. Box 10412
Palo Alto, CA 94303-0813

Mr. Terry Surles
Electricity Innovation Institute (E2I)
3412 Hillview Ave.
P. O. Box 10412
Palo Alto, CA 94303-0813

Dr. Dave Feder
Electrochemical Energy Storage Systems, Inc.
35 Ridgedale Avenue
Madison, NJ 07940

Mr. Jack Brown
ElectroEnergy, Inc.
30 Shelter Rock Road
Danbury, CT 06810

Mr. Michael Eskra
ElectroEnergy, Inc.
30 Shelter Rock Road
Danbury, CT 06810

Dr. Martin Klein
ElectroEnergy, Inc.
30 Shelter Rock Road
Danbury, CT 06810

Mr. Jamie Landi
ElectroEnergy, Inc.
30 Shelter Rock Road
Danbury, CT 06810

Mr. Chuck Whitaker
Endecon Engineering
347 Norris Court
San Ramon, CA 94583

Ms. Ndeye K. Fall
Energetics, Inc.
901 D Street, SW
Suite 100
Washington, DC 20024

Ms. Lauren Giles
Energetics, Inc.
7164 Columbia Gateway Drive
Columbia, MD 21046

Mr. Howard Lowitt
Energetics, Inc.
7164 Gateway Drive
Columbia, MD 21046

Mr. Brian Marchionini
Energetics, Inc.
901 D Street, SW
Suite 100
Washington, DC 20024

Mr. Rich Scheer
Energetics, Inc.
901 D Street, SW
Suite 100
Washington, DC 20024

Dr. Edward Skolnik
Energetics, Inc.
901 D Street, SW
Suite 100
Washington, DC 20024

Ms. Amber Gray-Fenner
Energy Communications Consulting
7204 Marigot Rd. NW
Albuquerque, NM 87120

Mr. R. B. Sloan
Energy United
P.O. Box 1831
Statesville, NC 28687

Dr. Sanjay Deshpande
EnerSys Inc
2366 Bernville Road
Reading, PA 19605

Mr. R. Kristiansen
EnerSys, Inc.
35 Loch Lomond Lane
Middleton, NY 10941-1421

Mr. Steven Eckroad
EPRI
1300 West WT Harris Blvd.
Charlotte, NC 28262-8550

Dr. Robert B. Schainker
EPRI
3412 Hillview Ave
P.O. Box 10412
Palo Alto, CA 94062

Mr. Doug Dorr
EPRI PEAC
942 Corridor Park Boulevard
Knoxville, TN 37932

Mr. Haresh Kamath
EPRI PEAC Corporation
942 Corridor Park Boulevard
Knoxville, TN 37932

Mr. Tom Key
EPRI-PEAC Corporation
942 Corridor Park Blvd.
Knoxville, TN 37932

Mr. Joe Waligorski
First Energy Corp.
76 S. Main Street
Akron, OH 44308

Mr. James P. Dunlop
Florida Solar Energy Center
1679 Clearlake Road
Cocoa, FL 32922-5703

Mr. Bob Zrebiec
GE Industrial & Pwr. Services
640 Freesom Business Center
King of Prussia, PA 19046

Mr. Nick Miller
General Electric Company
1 River Road
Building 2, Room 605
Schenectady, NY 12345

Mr. Declan Daly
General Electric Drive Systems
1501 Roanoke Blvd.
Salem, VA 24153

Dr. Raj M. Bharadwaj
General Electric Global Research
One Research Circle
ES 601
Niskayuna, NY 12309

Mr. Daniel P. Smith
General Electric Global Research
P.O. Box 8, ES-142
Schenectady, NY 12301

Mr. George Hunt
GNB Industrial Power
3950 Sussex Avenue
Aurora, IL 60504-7932

Mr. Robert Schmitt
GNB Industrial Power
3950 Sussex Ave.
Aurora, IL 60504

Mr. Steven Haagensen
Golden Valley Elec. Assoc., Inc.
758 Illinois Street
P.O. Box 71249
Fairbanks, AK 99701

Mr. Rick Winter
Halcyon Energy
42 Ardilla Road
Orinda, CA 94563

Mr. Philip Kunsberg
Haviland Holdings, Inc.
134 East Gate Drive
Suite B
Los Alamos, NM 87544

Mr. Clyde Nagata
Hawaii Electric Light Co.
P.O. Box 1027
Hilo, HI 96720

Ms. Jacqui L. Hoover
Hawaii Ocean Science & Technology Park
73-4460 Queen Kaahumanu Hwy., #101
Kailua-Kona, HI 96740-2632

Mr. Larry Meisner
HOPPECKE Batteries, Inc.
1960 Old Cuthbert Road Suite 130
Cherry Hill, NJ 08034

Dr. Mohammad Shahidehpour
Illinois Institute of Technology
3301 S. Dearborn
Chicago, IL 60616

Mr. Carl Parker
ILZRO
P.O. Box 12036
Research Triangle Park
Durham, NC 27709

Mr. Ron Myers
Imperial Oil Research Centre
3535 Research Road NW 2E-123
Calgary, Alberta T2L 2K8
CANADA

Mr. Ken Belfer
Innovative Power Sources
1419 Via Jon Jose Road
Alamo, CA 94507

Mr. André Bélanger
Institut de recherche d'Hydro-Quebec
1800 Boul. Lionel Boulet
Varennes, Quebec J3X 1S1
CANADA

Dr. Robert Wills
Intergrid Consulting
39 Union Street
Peterborough, NH 03458

Mr. A. Kamal Kalafala
Intermagnetics General Corp.
450 Old Niskayuna Road
P.O. Box 461
Latham, NY 12110-0461

Dr. Albert R. Landgrebe
International Electrochemical Sys &
Technology
B14 Sussex Lane
Long Neck, DE 19966

Dr. Patrick Moseley
International Lead Zinc Research
Organization Inc.
P.O. Box 12036
Research Triangle Park, NC 27709

Dr. Jerome F. Cole
International Lead Zinc Research
Organization, Inc.
P.O. Box 12036
Research Triangle Park, NC 27709-2036

Dr. Rosalind Volpe
International Lead Zinc Research
Organization, Inc.
P.O. Box 12036
Research Triangle Park, NC 27709-2036

Mr. Douglas Freund
Invensys Energy Management Division
2023 North Atlantic Avenue, #276
Cocoa Beach, FL 32926

Mr. Willie Ozbirn
Invensys Energy Solutions
1034 East Ash Street (62703)
P.O. Box 19424
Springfield, IL 62794-9424

Mr. Bob Haug
Iowa Association of Municipal Utilities
1735 NE 70th Avenue
Ankeny, IA 50021-9353

Mr. David Bertagnolli
ISO New England
One Sullivan Road
Holyoak,, MA 01040-2841

Ms. Imelda G. Francis
Just Do IT
21658 W. Ravine
Lake Zurich, IL 60047

Mr. Gerard H.C.M. Thijssen
KEMA Consulting Europe (KCE)
P.O. Box 9035
Arnhem, 6800ET
NETHERLANDS

Mr. Joseph M. Derby
Kerr-McGee Chemical LLC
P.O. Box 25861
Oklahoma City, OK 73125

Dr. Elton Cairns
Lawrence Berkeley National Laboratory
One Cyclotron Road
Berkeley, CA 94720

Dr. Joseph H. Eto
Lawrence Berkeley National Laboratory
1 Cyclotron Road
MS 90-4000
Berkeley, CA 94720

Dr. Frank R. McLarnon
Lawrence Berkeley National Laboratory
1 Cyclotron Road
MS 70-108B
Berkeley, CA 94720

Mr. J. Ray Smith
Lawrence Livermore National Laboratory
7000 East Avenue
L-644
P.O. Box 808
Livermore, CA 94551
925-422-7802

Dr. Susan M. Schoenung
Longitude 122 West, Inc.
1010 Doyle Street
Suite 10
Menlo Park, CA 94025

Mr. Patrick J. McGinnis
Machinery Research & Engineering
Directorate
NSWCCD-SSES, Building 77L
5001 South Broad Street
Philadelphia, PA 19112-1403

Mr. Jim Fiske
Magtube, Inc.
5735-B Hollister Ave.
Goleta, CA 93117

Mr. John Sawarin
McKenzie Bay International Ltd.
143 Windsor Avenue
London, Ontario N6C 2A1
CANADA

Mr. Rene Pardo
Mega-C Power Corporation
100 Caster Avenue
Vaughan, Ontario L4L 5Y9
CANADA

Mr. Lewis Taylor
Mega-C Power Corporation
100 Caster Avenue
Vaughan, ON L4L 5Y9
CANADA

Mr. Peter Donalek
Montgomery Watson Harza (MWH) Global
175 W Jackson Blvd, Floor 19
Suite 1900
Chicago, IL 60604-2814

Mr. Jagoron Mukherjee
MPR Associates, Inc.
320 King Street
Alexandria, VA 22311

Dr. Amit Singhal
Nanopowder Enterprises, Inc.
201 Circle Drive
Suite 102/103
Piscataway, NJ 08854

Dr. Norman T. Holcombe
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236-0940

Mr. Tony Schaffhauser
National Renewable Energy Laboratory
1617 Cole Boulevard
MS 6000
Golden, CO 80401

Mr. Steven P. Lindenberg
National Rural Elec Cooperative Assoc.
4301 Wilson Boulevard
SSER9-207
Arlington, VA 22203-1860

Mr. Charles H. Zimmerman
Naval Surface Warfare Center Carderock Division
Ship Systems Engineering Station, Building 4
Philadelphia Naval Business Center
Philadelphia, PA 19112-5083

Mr. Kae Kawana Pohe
Nevarest Research
443 Nevada Highway
Boulder City, NV 89005

Dr. Satish J. Ranade
New Mexico State University
Klish School of ECE
Box 3001, Dept. 3-O
Las Cruces, NM 88003

Mr. Andrew L. Rosenthal
New Mexico State University
Box 30001/Dept. 3SOL
Las Cruces, NM 88003-8001

Mr. Toyoo Ted Takayama
NGK Insulators, LTD
2-56 Suda-Cho
Mizuho-Ku, Nagoya-Shi 467-8530
JAPAN

Mr. Eddy Ozawa
NGK-Locke, Inc.
2525 Insulator Drive
Baltimore, MD 21230

Mr. Benjamin Norris
Norris Energy Consulting Company
2522 Promontory Cir.
San Ramon, CA 94526

Mr. Edward Torrero
NRECA Cooperative Research Network
4301 Wilson Boulevard, SS9-204
Arlington, VA 22203-1860

Mr. Clinton Winchester
NSWC Carderock Division, Code 644
9500 MacArthur Boulevard
West Bethesda, MD 20817-5700

Mr. Joseph H. Sayer
NYSERDA
17 Columbia Circle
Albany, NY 12203-6399

Mr. Michael A. Karnitz
Oak Ridge National Laboratory
P.O. Box 2008
MS 6186
Oak Ridge, TN 37831-6186

Dr. Brendan J. Kirby
Oak Ridge National Laboratory
P.O. Box 2008
MS-6070
Oak Ridge, TN 37831-6070

Mr. John Stoval
Oak Ridge National Laboratory
P.O. Box 2008
Bldg. 3147, MS-6070
Oak Ridge, TN 37831-6070

Dr. Salah Oweis
OWEITECH
4705 Hallowed Stream
Ellicott City, MD 21042

Mr. Todd Jaffe
Power Asset Brokers, LLC
3420 Keyser Road
Baltimore, MD 21208

Mr. Stan Sostrom
Power Engineers, Inc.
P.O. Box 777
3870 US Hwy 16
Newcastle, WY 82701

Mr. Joseph Szymborski
Powered-Up Solutions, Inc.
4210 Kingsley St.
Clermont, FL 34711

Mr. Roger Flynn
Public Service Co. of New Mexico
Alvarado Square MS-2838
Albuquerque, NM 87158

Mr. Jerry Neal
Public Service Co. of New Mexico
Alvarado Square MS-BA52
Albuquerque, NM 87158

Mr. Scott Hassell
RAND Corporation
1200 South Hayes Street
Arlington, VA 22202-5050

Mr. James T. Reilly
Reilly Associates
P.O. Box 838
Red Bank, NJ 07701

Mr. Gregg Renkes
Reliable Power Inc.
2300 Clarendon Blvd.
Suite 401
Arlington, VA 22201

Dr. Malcolm T. Jacques
Reliable Power, Inc.
2300 Clarendon Boulevard
Suite 401
Arlington, VA 22201

Mr. Matthew Karcher
Reliable Power, Inc.
2300 Clarendon Boulevard
Suite 401
Arlington, VA 22201

Mr. John P. Venners
Reliable Power, Inc.
2300 Clarendon Boulevard
Suite 401
Arlington, VA 22201

Ms. Nisha Desai
Ridge Energy Storage & Grid Services
3555 Timmons
Suite 650
Houston, Tx 77027

Mr. Lawrence E. Rinehart
Rinehart Motion Systems, LLC
25977 SW Canyon Creek Road
Suite D
Wilsonville, OR 97070

Mr. Markus Becker
RWE North America
555 12th Street
Suite 630
Washington, DC 20004

Mr. Bradford Roberts
S&C Electric
5251 W. Franklin Drive
Franklin, WI 53132

Dr. Guy Chagnon
Saft America, Inc.
107 Beaver Court
Cockeysville, MD 21030

Mr. James McDowall
Saft America, Inc.
3 Powdered Metal Drive
North Haven, CT 06473

Mr. Michael C. Saft
Saft America, Inc.
107 Beaver Court
Cockeysville, MD 21030

Ms. Mindi J. Farber-DeAnda
SAIC
8301 Greenboro Dr. 5th floor
McLean, VA 22102

Mr. G. E. Palomino
Salt River Project
P.O. Box 52025
MS PAB 357
Phoenix, AZ 85072-2025

Mr. Fred H. Schwartz
San Francisco Public Utilities Commission
1155 Market Street, 4th Floor
San Francisco, CA 94103

Mr. Leonard Lansing
Satcon Power Systems
835 Harrington Court
Burlington, Ontario L7N 3P3
CANADA

Dr. Alex Q. Huang
Semiconductor Power Electronics Center
(SPEC)
North Carolina State University
Campus Box 7571
Raleigh, NC 27695-7571

Mr. Larry Markel
Sentech
700 S. Illinois Ave
Suite A201
Oak Ridge, TN 37830

Mr. Jonathan Hurwitch
Sentech, Inc.
4733 Bethesda Avenue
Suite 608
Bethesda, MD 20814

Mr. Lumas Kendrick, Jr.
SENTECH, Inc.
4733 Bethesda Avenue
Suite #608
Bethesda, MD 20814

Mr. Kurt W. Klunder
Sentech, Inc.
4733 Bethesda Avenue
Suite 608
Bethesda, MD 20814

Ms. Krista Long
Sentech, Inc.
4733 Bethesda Avenue
Suite 608
Bethesda, MD 20814

Dr. Rajat K. Sen
Sentech, Inc.
4733 Bethesda Avenue
Suite 608
Bethesda, MD 20814

Mr. Srikesh Sridharan
Sentech, Inc.
4733 Bethesda Avenue
Suite 608
Bethesda, MD 20814

Mr. Richard N. Schweinberg
Southern California Edison
6070 N. Irwindale Avenue
Suite I
Irwindale, CA 91702

Dr. Katsuji Emura
Sumitomo Electric USA, Inc
21221 S. Western Avenue
Suite 200
Torrance, CA 90501

Mr. Anthony Price
Swanbarton Limited
Barton House
Swan, Malmesbury
Wiltshire, SN160.0LJ
UNITED KINGDOM

Dr. Philip C. Symons
Symons/EECI
16534 W. Cibola Lane
Surprise, AZ 85387

Mr. Harold Gotschall
Technology Insights
6540 Lusk Boulevard
Suite C-102
San Diego, CA 92121

Mr. Daniel Mears
Technology Insights
6540 Lusk Boulevard
Suite C-102
San Diego, CA 92121-2767

Mr. Philip Johnson
The Boeing Company
P.O. Box 3707
MC 2T-50
Seattle, WA 98124-2207

Mr. Haukur Asgeirsson
The Detroit Edison Company
2000 2nd Avenue
435 SB
Detroit, MI 48226-1279

Mr. Charles E. Bakis
The Pennslyvania State University
212 Earth & Energy Sciences Building
University Park, PA 16802

Mr. Tom Anyos
The Technology Group, Inc.
63 Linden Avenue
Atherton, CA 94027-2161

Mr. Bill Ropenecker
Trace Engineering Division
5916 195th Northeast
Arlington, WA 98223

Ms. Melissa Reading
Trinity Flywheel
6745D Preston Avenue
Livermore, CA 94550

Mr. Jim Drizos
Trojan Battery Company
12380 Clark Street
Santa Fe Springs, CA 90670

Dr. Joseph Hoagland
TVA/Public Power Institute
P.O. Box 1010
MS PPI-1A
Muscle Shoals, AL 35662-1010

Dr. Gerald P. Ceasar
U.S. Department of Commerce
NIST
100 Bureau Drive, MS 4720
Gaithersburg, MD 20899-4720

Mr. Gil Bindewald
U.S. Department of Energy
1000 Independence Avenue, SW
TD-2D, FORS
Washington, DC 20585

Mr. Gary D. Burch
U.S. Department of Energy
1000 Independence Avenue, SW
Washington, DC 20585

Mr. John B. Cadogan
U.S. Department of Energy
1000 Independence Avenue, SW
EE-2B, FORS
Washington, DC 20585

Mr. James G. Daley
U.S. Department of Energy
1000 Independence Avenue, SW
TD-2 FORS
Washington, DC 20585

Mr. Tien Q. Duong
U.S. Department of Energy
1000 Independence Avenue, SW
EE-2G, FORS
Washington, DC 20585

Mr. Peter R. Goldman
U.S. Department of Energy
1000 Independence Avenue, SW
EE-2B, FORS
Washington, DC 20585

Mr. Sigmund Gronich
U.S. Department of Energy
1000 Independence Avenue, SW
EE-2H, FORS
Washington, DC 20585

Dr. Imre P. Gyuk
U.S. Department of Energy
1000 Independence Avenue, SW
TD-2 FORS
Washington, DC 20585

Ms. Deborah A. Haught
U.S. Department of Energy
1000 Independence Avenue, SW
EE-2D FORS
Washington, DC 20585

Ms. Patricia A. Hoffman
U.S. Department of Energy
1000 Independence Avenue, SW
EE-2D, FORS
Washington, DC 20585

Mr. Richard J. King
U.S. Department of Energy
1000 Independence Avenue, SW
EE-2A, FORS
Washington, DC 20585

Mr. Philip N. Overholt
U.S. Department of Energy
1000 Independence Avenue, SW
TD-2, FORS
Washington, DC 20585

Mr. William P. Parks
U.S. Department of Energy
1000 Independence Avenue, SW
TD-1, FORS
Washington, DC 20585

Mr. James E. Rannels
U.S. Department of Energy
1000 Independence Avenue, SW
EE-2J, FORS
Washington, DC 20585

Mr. Neil P. Rossmeissl
U.S. Department of Energy
1000 Independence Avenue, SW
EE-2E, FORS
Washington, DC 20585

Mr. Dan T. Ton
U.S. Department of Energy
1000 Independence Avenue, SW
EE-2A, FORS
Washington, DC 20585

Dr. Samuel F. Baldwin
U.S. Department of Energy
1000 Independence Avenue, SW
EE-11, FORS
Washington, DC 20585-0121

Mr. Dan Sanchez
U.S. Department of Energy - Albuquerque
Operations Office
Pennsylvania & H Street
Kirtland Air Force Base, NZ - 384-3
Albuquerque, NM 87185

Mr. Eric M. Lightner
U.S. Department of Energy,
Communications and Control Program
1000 Independence Avenue, SW
TD-2 FORS
Washington, DC 20585

Mr. Wayne Taylor
U.S. Navy
Code 83B000D, NAWS
China Lake, CA 93555

Dr. Edward Beardsworth
UFTO
951 Lincoln Avenue
Palo Alto, CA 94301-3041

Mr. Richard Lemmons
United States Air Force
OO-ALC/LIPC
6040 Gum Lane
Hill AFB, UT 84056-5825

Dr. Bor Yann Liaw
University of Hawaii
1680 East West Road
Post 112A
Honolulu, HI 96822

Mr. Sandeep Nayak
University of Maryland
College Park, MD 20742

Dr. Mariesa L. Crow
University of Missouri - Rolla
305 McNutt Hall
Rolla, MO 65409-0040

Mr. John Herbst
University of Texas - Austin, CEM
10100 Burnet Road
Building 133
Austin, Tx 78712

Mr. Bob Lasseter
University of Wisconsin
1415 Engineering Dr.
Home- 2913 Walnut Wood Ct. 53711
Madison, WI 53706

Dr. John Woodthorpe
Urenco Power Technologies
Virginia Avenue, NW
Suite 610
Washington, DC 20037

Dr. John Woodthorpe
Urenco Power Technologies
Capenhurst, Chester CH1 6ER
UNITED KINGDOM

Mr. Alan Palin
Urenco Power Technologies, Ltd.
Capenhurst, Cheshire CH1 6ER
UNITED KINGDOM

Mr. David St. Angelo
Valence Technology, Inc.
6504 Bridge Point Parkway
Suite 415
Austin, Tx 78730

Mr. Rick Lawrence
Valley Forge Corporate Center
2621 Van Buren Avenue
Norristown, PA 19403

Mr. Mark Kuntz
VRB Power Systems Inc.
3N080 Morningside Avenue
West Chicago, IL 60185

Mr. Michael Benke
Xantrex Technology, Inc.
161-G South Vasco Road
Livermore, CA 94550

Mr. Rusi Patel
Xenergy/KEMA Consulting
3 Burlington Woods
Burlington, MA 01803

Mr. Yoshiyasu Yamamoto
YC Consulting
6102 Shelby Street
Indianapolis, IN 46227

Mr. Henry Zaininger
Zaininger Engineering Co.
9959 Granite Crest Court
Granite Bay, CA 95746

Mr. Michael Hughes
ZBB Technologies Inc.
N93 W14475 Whittaker Way
Menomonee Falls, WI 53051

Mr. Peter Lex
ZBB Technologies, Inc.
N93 W14475 Whittaker Way
Menomonee Falls, WI 53051

Mr. Greg Nelson
ZBB Technologies, Inc.
N93 W14475 Whittaker Way
Menomonee Falls, WI 53051-1653

Mr. Robert Parry
ZBB Technologies, Inc.
N93 W14475 Whittaker Way
Menomonee Falls, WI 53051

MS0512/2500	Thomas E. Blejwas (1)
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