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# Estimating Electricity Storage Power Rating and Discharge Duration for Utility Transmission and Distribution Deferral

# A Study for the DOE Energy Storage Program

Jim Eyer, Joe Iannucci, and Paul C. Butler

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

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# Estimating Electricity Storage Power Rating and Discharge Duration for Utility Transmission and Distribution Deferral

## A Study for the DOE Energy Storage Program

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

Paul Butler
Power Sources Development Department
Sandia National Laboratories
P.O. Box 5800
Albuquerque, NM 87185-0614

**Abstract**

This report describes a methodology for estimating the power and energy capacities for electricity energy storage systems that can be used to defer costly upgrades to fully overloaded, or nearly overloaded, transmission and distribution (T&D) nodes. This "sizing" methodology may be used to estimate the amount of storage needed so that T&D upgrades may be deferred for one year. The same methodology can also be used to estimate the characteristics of storage needed for subsequent years of deferral.

# Acknowledgement

The authors wish to acknowledge the U.S. Department of Energy, Energy Storage Systems Program for the support of this work. We also gratefully acknowledge the review of this report by John Boyes and Nancy Clark, Sandia National Laboratories.

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## In Memoriam

On November 4, 2004, the electricity storage, renewable energy, and distributed energy resources communities lost a great friend, effective advocate, and technological pioneer, Joe Iannucci.

Despite the odds and disbelieving peers, Joe enthusiastically and effectively championed renewables beginning in the 1970s and distributed energy resources beginning in the 1980s. Toward the end of his career Joe took on the challenge of understanding the benefits provided by distributed electricity storage.

Joe's legacy is now blossoming—the opportunities for these evolving technologies are real, significant, and growing.

# Table of Contents

## Table of Figures



## Table of Tables

# Acronyms

| | |
|---|---|
| DER | Distributed Energy Resource |
| DES | Distributed Energy Storage |
| DG | Distributed Generation |
| DOE | Department Of Energy |
| DUA | Distributed Utility Associates |
| EPRI | Electric Power Research Institute |
| ESS | Energy Storage Systems |
| IEEE | Institute of Electrical and Electronics Engineers |
| PQ | Power Quality |
| T&D | transmission and distribution |
| VAR | volt-ampere reactive |

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# Section 1. Introduction

## 1.a. Purpose

The purpose of this study was to develop a methodology for distribution engineers to use when evaluating the amount of distributed energy storage (DES) needed to defer transmission and/or distribution (T&D) capacity upgrades. The emphasis of this research was on technical design and operations, with only incidental treatment of financials and specific modular energy storage technologies.

There are two key drivers for this study:

- The business environment in the evolving U.S. electricity marketplace requires more flexible, robust, and diverse ways to respond to accelerating change and uncertainty. One such option is the use of distributed energy resources (DERs) to reduce the cost per kW of peak load served. Distributed electricity storage may be especially well suited to this type of application.

- Utilities need credible, standardized, and vetted means to evaluate the operational viability of DES. The framework described herein addresses part of that need by focusing on the most fundamental characteristics of DES to be used for T&D deferral: DES power rating and energy storage capacity.

This report is the fourth in a series funded by the U.S. Department of Energy, Energy Storage Systems (ESS) Program implemented by Sandia National Laboratories. These reports present detailed analysis of innovative, high value uses for modular electric energy storage.[1][2][3]

## 1.b. Scope

The key elements of a DES "sizing" methodology for estimating the characteristics of electric energy storage equipment so that a planned or needed utility T&D capacity upgrade/expansion may be deferred. The methodology yields the estimated amount of energy storage necessary to defer the T&D upgrade for one year. Prospects of storage to defer the same upgrade at the same site must be evaluated separately for each year of deferral using this methodology.

The methodology focuses on estimating two key storage system characteristics: a) power output, and b) discharge duration (or, the amount of energy that must be stored). Sizing estimates are made without regard to storage-system cost. In fact, the sizing exercise is required before an acceptable or target DES cost can be estimated.

By design, the methodology described in this document is generic. Each utility must use the techniques described herein within the broader context of their existing distribution planning framework and philosophy to evaluate the technical and financial merits of storage for their organization and specific circumstances.

It is important to note that the focus of this study is on distribution and subtransmission systems. The key reason for this focus is that criteria used for high voltage, bulk transmission capacity planning are somewhat different than those used to justify a subtransmission or distribution upgrade. So in this report, the term T&D refers to subtransmission and distribution.

### 1.b.1. Related Topics Beyond the Scope of this Report

#### *1.b.1.a. Benefits from Use of Energy Storage*

Though not the focus of this study, readers are encouraged to be familiar with the range of monetary benefits that may accrue in any particular situation/location if energy storage is used. This is important because engineers considering the use of energy storage for T&D deferral may be able to ascribe additional benefits to a storage plant which they might specify for T&D deferral. A recent publication by Sandia for the U.S. Department Of Energy (DOE) provides an overview of those benefits.[4]

#### *1.b.1.b. Utility Financials*

Detailed coverage of utility financials is beyond the scope of this evaluation. However, a cursory understanding of those financials is important to understand the merits of electricity storage used to defer a T&D upgrade.

Consider an example: a somewhat typical upgrade involves adding 4,000 kW to a 12,000-kW T&D node. The ultimate capacity is 16,000 kW. The project cost is $260 per kW *added* (see Appendix A).[5][6][7] The total project cost is $260/kW * 4,000 kW = $1,040,000.

When evaluating prospects for energy storage to defer a T&D upgrade, it is necessary to calculate the *annual* carrying cost for the upgraded equipment. A "fixed charge rate" is often used to calculate that annual carrying cost (also known as revenue requirement). A representative fixed charge rate is 0.13.[8]

The fixed charge rate is a simple way to represent the total annual costs (per $ invested) associated with owning capital equipment, including interest, dividends, return of capital, income tax, property tax, and insurance. The fixed charge rate is used to calculate a "levelized" annual cost akin to an annuity.

Applying the fixed charge rate to the example cost above, the *annual* cost to own the upgraded equipment is 0.13 * $1,040,000, or just over $135,000/year. Similarly, the annual cost *per kW* is $260/$kW_{added}$ * 0.13 = $34/kW-year.

The value $260/$kW_{added}$ is a representative cost based on a review of the literature.[5][7][9] However, in a few cases, the cost per $kW_{added}$ may be as much as three times this value. Thus, depending on the specific circumstances related to the location, equipment, and load conditions, the range in cost for additional T&D capacity may be significant.

Another important note is that this document does not propose a specific way to pay for DES equipment. There are three primary approaches: 1) lease, 2) rent, or 3) buy. There are significant regulatory, accounting and financial implications associated with any approach.

#### *1.b.1.c. Storage Technologies and Costs*

This report does not directly address storage systems' cost. However, before the total cost for a storage system can be established, an estimate must be made of the storage system's rating. Reference 10 is recommended as a source of information about storage system prices and costs.[10]

Though no specific storage technology is assumed for this document, in general terms modular energy storage used for T&D deferral is assumed to provide high quality power, reliably. Power from storage systems must have a high power factor, good frequency and voltage stability, and low harmonics. Volt-amp reactive (VAR) support capability may provide additional benefits. Systems should be very reliable; ideally they must be as reliable as the grid service near the location of interest.

The authors contend that there are several existing and emerging electricity storage technologies with the above characteristics. That premise is based, in part, on extensive utility industry experience with over 100,000 battery storage systems used for *on-site* loads at substations, especially for emergency power needs (i.e., must be very reliable). These systems are comprised of battery banks with power outputs that are typically in the tens of kWs, with discharge durations of eight hours.[11][12]

Specifically, well-maintained battery storage systems used at substations (to serve on-site loads) provide very reliable power; availability usually exceeds 99%, and "two nines" reliability is common.[13] And, electricity storage technology improvement and development is ongoing.[10]

#### *1.b.1.d. Multi-year T&D Upgrade Deferrals*

The methodology described in this document is used to calculate the amount of storage needed to defer a T&D upgrade for *one year*. If storage is to be used at the same location in subsequent years, the single year evaluation described in this document must be undertaken for each of those subsequent years. The annual benefits from each kW of storage decrease rapidly for subsequent years of T&D deferral at the same location.[12][13][14][15] In general, this is due to the rapidly diminishing annual benefits from a fixed DES capacity ($/kW-yr) as load grows.

#### *1.b.1.e. Planning Uncertainty*

This document provides limited coverage of the uncertainties that may affect energy storage system sizing, however: 1) key sources of uncertainty are identified, and 2) when applicable, the authors indicate situations for which a sizing evaluation could include sensitivities or adjustments to account for uncertainty.

### 1.b.1.f. Relocatable Modular Storage

If a storage system can be relocated easily, then it could be used at several locations. For example, storage could be used at one location where peak demand occurs during summer, and then moved to another location where peak demand occurs in the winter. Or, the storage could be moved to different locations in different years. Such movement increases the life cycle benefits per kW of storage, perhaps significantly.

### 1.b.1.g. DES Used to Increase Capacity of Existing T&D Equipment

The methodology described in this document is used to size DES to add real power capacity commensurate with real power requirements of loads served. Though the topic is beyond the scope of this document, readers should note that DES can also be used to increase the load carrying capacity of *existing* T&D equipment by improving the "performance" of the equipment. One example is known as damping: a relatively small amount of DES is used to attenuate frequency variations so the T&D equipment can carry more load. Additional coverage of this topic is provided in the Electric Power Research Institute-Department Of Energy (EPRI-DOE) Handbook of Energy Storage for Transmission and Distribution Applications.[16]

## 1.c. Candidate Sites and Circumstances

Though a storage sizing evaluation could be undertaken for any T&D node, presumably certain nodes may have been designated as "hot spots" by distribution engineers during normal distribution planning. Stated another way, the authors do not propose DES as a solution seeking a need. Rather, the key objective of this study is to enable a preliminary evaluation of the relative merits of DES as an option during the normal T&D planning process. Please see Section 5.a. for criteria to use to identify candidate locations.

Readers will note that there is significant overlap between a) the energy storage sizing exercise, and b) the normal T&D planning process. For example, when deciding whether to proceed with a given T&D upgrade, a prime consideration is the degree to which load may grow beyond the existing T&D capacity during the next peak load season. That same criterion is used to estimate the power requirements for the DES system which could be used to defer the T&D upgrade for one year.

## 1.d. Energy Storage Plant Rating – Two Characteristics

As with any equipment that generates, converts, or transfers electricity, a key characteristic is the equipment's power rating: the rate at which the equipment can transfer, convert, or generate electric energy (for storage, power indicates the rate at which the system can discharge energy). A storage plant's power rating is expressed in units of kW or MW.[1]

[1] For this document, units of kW and MW–true power–are used, though units of kVA may be more appropriate.

Storage systems have another, equally important characteristic. That characteristic is related to the fact that storage systems must contain enough stored electric energy[2] to operate for as long as needed, though the amount of energy is limited. So, the other key design characteristic for storage systems is discharge duration–expressed in units of time, ranging from seconds to hours. Discharge duration is the amount of time that the storage plant can discharge at its rated power without being recharged.

The two characteristics are sometimes called power and energy, respectively, where energy (kWh or MWh) = power (kW or MW) times discharge duration (hours). Consider a simple example: a one kilowatt storage system. For that system to operate for three hours (a three-hour discharge duration) at its full power rating, it must have enough storage capacity to store three kilowatt-hours of electric energy (net of losses).

As a convention, when energy output is discussed, the amount of energy discharged is net of losses associated with storing and discharging the energy. Typically, the so-called "round-trip" energy storage losses are on the order of 10% to 30%. (Often, storage systems are characterized as having a specific round-trip efficiency).

## *1.e. Introduction to Utility T&D Deferral*

In the future, electric utilities may find it advantageous and even prudent to use modular electricity storage located downstream from overloaded, or nearly overloaded, transmission or distribution equipment to reduce peak loading. Some effects of this approach may include:

- a T&D upgrade is deferred;
- reduced T&D energy losses;
- improved utilization for existing T&D equipment during peak demand periods;
- reduced wear and tear on distribution equipment (e.g., due to thermal stressing), possibly leading to reduced maintenance expenses and/or increased equipment life.

### 1.e.1. Serving Marginal Load to Defer T&D Upgrade Investment

For this methodology, the single-year T&D deferral benefit is assumed to be the financial carrying cost that is avoided because the upgrade is deferred. Further, it is assumed that DES is used so that the upgrade can be deferred.

Consider the previous example in section 1.b.1.b. and Appendix A: A distribution upgrade involving a 12,000-kW node that will be upgraded so it can accommodate 16,000 kW of load represents an increase of 4,000 kW, or 33%.

[2] In the strictest sense, energy storage could also include diesel fuel, gasoline, natural gas, and propane stored locally. It could also include thermal energy. In the context of this report, electric energy storage, or energy storage, refers to a device: a) for which energy to be stored is supplied to the device in the form of electricity, and b) that discharges electric energy. Note that thermal energy storage used to reduce peak demand has very similar effects as those of electricity storage, from a utility perspective.

The distribution upgrade installed cost is \$260/kW *added,* for a total of \$1,040,000.
The annual carrying cost for the upgrade is 0.13 * \$1,040,000 = about \$135,000.
In simplest terms, that is the financial benefit associated with a one-year deferral of the upgrade.

To defer an upgrade for one year; if peak load in the previous year was almost equal to the existing distribution equipment's rating, then assume that the DES power output must be equal to the expected load growth for the next year.

Continuing with the example: if load growth on the circuit is 2.5% per year, then load growth would be 12,000 kW *0.025 = 300 kW for the next year. In this document, that value is referred to as the design load.

The key point is that installing 300 kW of storage allows the utility to avoid a one time charge of \$135,000. From the perspective of utility ratepayers, that is a one-time, single-year benefit of \$135,000 for a storage plant with a power rating of 300 kW. The storage is worth \$135,000/300 kW = \$450/kW of storage.

Stated another way, if the storage system can be owned, leased, or rented for less than \$450/kW for one year, then the storage system may be a cost-effective[3] alternative to the upgrade, for one year.

That conclusion does not include consideration of: a) storage charging and maintenance costs, b) storage reliability, c) load growth uncertainty, and d) benefits not related to deferrals such as energy time-shifting.

For the foreseeable future, it is likely that the storage systems available for T&D deferral will cost more than \$450/kW. However, if such a DES is transportable such that it may be used for other upgrade deferrals at different locations in different years, then the life cycle benefits may be significant. For example, if three such deferrals are made at an average annual benefit of \$450/kW, then the life cycle benefits would be \$1,350/kW (without regard to the time-value of money).

And, in some locations a permanent DES system may provide other possibly significant benefits for several years after a T&D upgrade is completed, such as energy time-shift, *system* peak demand reduction, spinning reserve, local power quality and reliability enhancements, etc.

Depending on circumstances, other types of DERs could also be used. Distributed energy resources include DES, distributed generation (DG), and geographically-targeted demand management and energy efficiency.

[3] In the utility sector, cost-effective means: a) the utility earns its authorized rate of return; and b) the option provides a given level of service (per regulations) for the lowest total cost to the utility's ratepayers.

# Section 2. Storage Power Rating Estimation

## *2.a. Introduction*

This section describes the elements of the analysis to estimate a storage system's power rating. In simplest terms, the amount of power needed (from the storage system) at a given hot spot is equal to the portion of the peak electric demand which exceeds the load carrying capacity at that hot spot (projected overload). Though theoretically a storage system's power rating is equal to the projected overload, there may be circumstances for which: a) a lower storage power rating may be acceptable, or b) a higher storage power rating may be needed.

Consider an example: for a circuit with a rating of 11.6 MW, the expected peak load for the next peak season is 11.8 MW; the projected overload is 200 kW (11.8 MW - 11.6 MW). Unless additional design considerations must be addressed, the design load is assumed to be equal to the projected overload.

Needless to say, making a final decision about a storage system's power rating is not that simple. To one extent or another, design load must account for several factors such as load growth-related uncertainty, weather-related uncertainty, the mix of loads being served (and the "cost" if there are outages), the cost associated with overloading (of the respective T&D node), special characteristics of local T&D equipment, storage system reliability, and organization-specific engineering preferences.

Consider another simple example: the projected overload on the circuit described above is 200 kW. Assume that there is a 20% chance that a 75-kW block load will be added to the circuit before the next peak season has passed. If so, engineers may want to add 75 kW to the projected overload, for a design load of 275 kW.

## *2.b. Data Requirements*

Data used to estimate the required storage power output (design load) should be similar to data used for normal distribution planning, though additional criteria may be needed for the energy storage sizing analysis for specific circumstances. For example, it may be important to consider the power quality impacts of storage, including the ability to provide "VAR support," storage system response time (rate at which power can be ramped up and down), or storage plant footprint and volume, if space is a limiting factor.

### 2.b.1. Base Year Peak Load

An important data item used in this methodology is the base year peak load; it is the maximum load during the year before the T&D upgrade is needed.

### 2.b.2. Load Growth

Load growth–coupled with the base year peak load–is a critical criterion for estimating design load. In most cases, load growth is estimated as a function of the historic peak load for the T&D node of interest. So, the historic peak demand value will probably be required, especially if the analyst will perform sensitivity evaluations.

#### 2.b.2.a. Block Load Additions

When establishing the design load, regard must be given to any significant block load additions that may be added to peak demand unexpectedly during the year of interest. Such block loads may include housing developments, commercial buildings, industrial or agricultural operations, etc.

Note that modular energy storage may be a superior solution–on a risk-adjusted cost basis –if there is uncertainty about whether or when block loads will materialize or be removed from the system, especially if the upgrade to be deferred is expensive.

#### 2.b.2.b. Standard Load Growth

Standard (or core) load growth is the nominal increase in peak load that occurs for reasons other than addition of block loads. Of specific interest when estimating the necessary power rating of a storage system is the expected peak load growth between the previous peak demand season and the upcoming peak demand season. For very cursory evaluations, the load growth rate suggested by a trend line might suffice. If so, then peak loads for the previous several years could be used to estimate an annual average peak load growth rate.

A more sophisticated approach is to use adjustments to the average or expected load growth rate to reflect more extreme cases. One example, to get a conservative result, is to use the highest load growth rate observed in recent years rather than an average over the last several years. Another example is an adjustment of the projected load growth so it reflects a one-year-in-ten temperature extreme. In some cases, a similar adjustment may also be warranted for relative humidity. To do that, historic load and coincident weather data (temperature and/or relative humidity) is needed as well as the one-year-in-ten temperature values.

### 2.b.3. T&D Equipment Rating

A key parameter for the evaluation is the maximum load that the T&D equipment to be upgraded can serve. In some cases, two ratings are considered: 1) nominal rating, and 2) what is sometimes called the emergency rating. The former is the maximum rating under normal conditions; it might be called the design point or the nameplate rating. The second reflects an incremental amount of load carrying capacity that can be used for short periods of time without significant damage to equipment.

## 2.c. Calculating Storage Power Rating Required

To begin the process of estimating the design load, the estimated load growth (on the T&D node of interest) is added to the historic peak load. The result is compared to the rating of the T&D equipment to estimate the degree to which peak load will exceed the T&D rating, i.e., projected overload. This is shown graphically in Figure 1.

In that example, the circuit can accommodate 11.6 MW of load (nominal). Peak demand in the base year (year 2003) was 11.51 MW. Assuming that peak load will grow 2.5%, the expected peak load during the next year (2004) would be 11.74 MW; 140 kW above the T&D rating of 11.6 MW, so 140 kW is the projected overload.

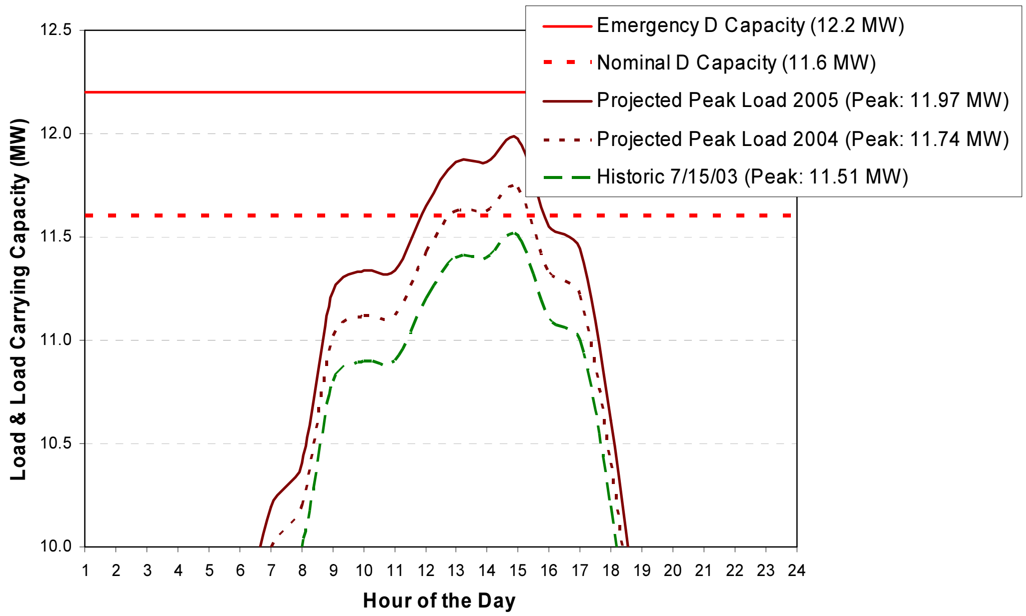


**Figure 1. Hourly Load for Highest Load Day in Summer, base Year Plus One and Plus Two Years of Projected Load Growth, Relative to Nominal and Emergency Distribution (D) Load Carrying Capacity.**

If the design load is equal to the projected overload (140 kW), and if the peak load in the next year happens to be exactly as projected, then when peak demand occurs, the circuit will carry load at its nominal rating of 11.6 MW and the storage will serve 140 kW.

### 2.c.1. Establishing Design Load

The foregoing describes a simple, deterministic approach to evaluating the power capacity for a storage system used to defer a T&D upgrade. As appropriate, engineers should apply expertise similar to that used for conventional T&D capacity planning including power engineering principles, art and judgment, rules-of-thumb, and utility-specific design preferences. Perhaps the most important adjustment is for extreme temperature. If the projected overload does not reflect the possibility of extreme temperatures, then the design load should.

With regard to the annual load growth rate used to establish the projected overload, for this exercise it may be prudent to use the highest annual load growth (rate) experienced in recent years rather than using an annual average rate. It is also important to account for possible or uncertain block load additions.

## *2.d. Other Engineering Considerations*

### 2.d.1. T&D Nominal Rating versus Emergency Rating

Consideration of the tradeoffs between lower loading/less risk and higher loading/more risk for T&D equipment is not addressed in this document.

However, use of modular resources enables distribution engineers, planners, and operators to make a number of trade-offs for greater planning and operational flexibility.

For example, to the extent appropriate, distribution engineers may perform storage power rating evaluations in ways that include consideration of the T&D equipment's emergency rating rather than the planning or nominal rating. In fact, the authors' ultimate vision involves distribution engineers having the means to understand trade-offs between several important decision criteria–including costs related to possible T&D equipment damage–when deciding which option, if any, to use to serve load on the margin.

### 2.d.2. Storage System Modularity

The storage power rating could be influenced by the degree to which the storage system is modular. If additional load-carrying capacity (power) can be added to a storage system quickly and easily, then the initial estimate of storage power capacity required may be reduced. In theory, it may be possible to add load-carrying capacity if and when needed.

Modular systems also reduce the chance of complete failure. Ideally, modules that fail can be replaced while most of the system continues to operate. Modular systems also allow for rapid redeployment from locations where high demand is unlikely to locations with more critical circumstances.

# Section 3. Storage Discharge Duration Estimation

## *3.a. Introduction*

This section addresses the analysis needed to estimate the storage system discharge duration: the amount of time that storage must be able to discharge energy, at the design power output rating, without recharging. A key premise for this approach is that modular energy storage systems are capable of what electricity generation engineers call "load-following." That is, the storage system can vary power output almost instantaneously as required to serve load.

An implicit assumption is that the storage system can either: a) monitor line conditions and respond automatically when and as needed, or b) distribution system operators have the means to monitor the node served by the storage system, and to communicate with and control the DES power output.

Readers should note that the analysis methodology described yields results that are specific to one location in one year. If storage is to be used for subsequent years at the same location, then the evaluation must be undertaken for each additional year to account for load growth. Normally, total power and discharge duration must be increased in each subsequent year, as load grows and as the peak load broadens over time. Exceptions to this rule are locations: a) that experience load reduction, or b) with no load growth.

Discharge duration is estimated based almost entirely on the shape of the demand profile expected when peak demand occurs at the T&D node of interest.

In addition to being a primary engineering criterion, discharge duration is a primary or even predominant element of storage system cost.

The primary steps for this evaluation are:

1. Establish the design load profile;
2. Based on the design load profile, estimate the design discharge duration;
3. Adjustments, if any, are made to the design discharge duration to establish the storage discharge duration to be specified.

In some cases, utilities have pre-defined load profiles for capacity planning. If not, then historic data are used to identify load profiles that represent the hourly loads that might occur during periods of maximum demand.

## *3.b. Data Requirements*

### 3.b.1. Hourly Load Profiles

The key data needed for this evaluation are historic hourly load data for the T&D hot spot being evaluated, for days during the peak demand season. The profiles of interest are those with the broadest peaks. Consider an example illustrated in Figure 2. This figure shows hourly loads for days that have especially broad demand peaks. Hourly loads are plotted for July 15, 2003, August 1, 2001, and June 22, 1999.

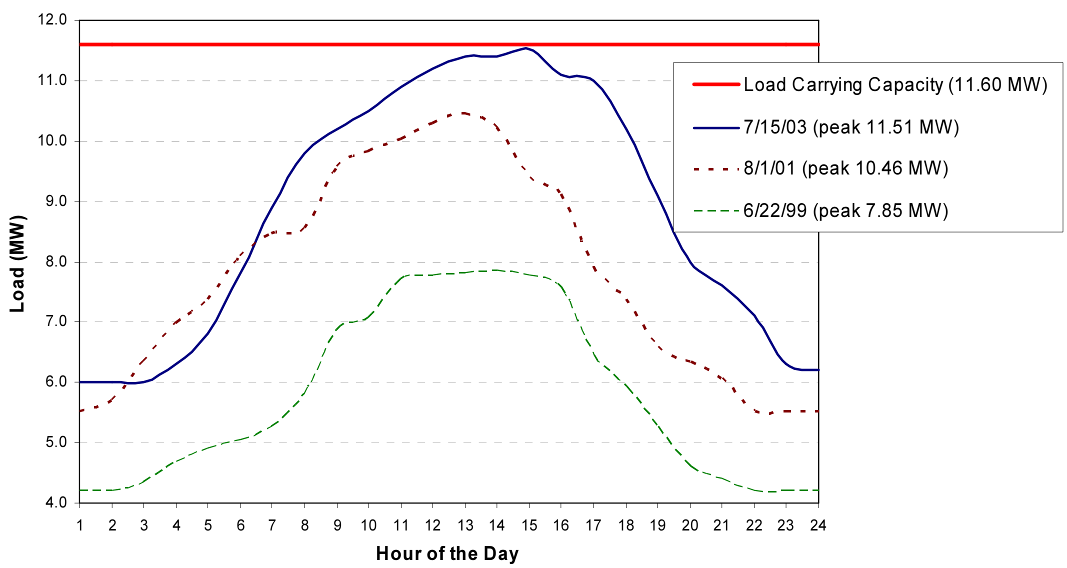


**Figure 2. Hourly Load Profiles for Three Days with Broad Peaks.**

### 3.b.2. Other Data Needed

- Base year peak load,
- Load growth expected by the next peak demand season–as described in Section 2.b.2., and
- T&D equipment's load carrying capacity (rating).

## *3.c. Design Load Profile*

### 3.c.1. Introduction to Establishing a Design Load Profile

The objective of the next step in the storage sizing methodology is to characterize hourly loading conditions that might occur on a day or days when maximum demand takes place. Note that in this context, maximum demand is the design load, as described in Section 2. In some cases, such design load profiles–used for T&D or even electric supply planning–exist for a given utility or region. If so, those *may* be appropriate for the discharge duration estimation process. Appropriate engineering judgment should be applied when making that decision.

If a predefined design load profile is not used, then a key to establishing the design load profile is to identify and evaluate historic load profiles that reflect possible loading conditions during the season when peak demand occurs. Estimating design discharge duration using the historic load profile with the broadest peak will yield a conservative estimate that is as robust as possible, without making additional assumptions and adjustments for factors such as possible block load additions or changes in energy use patterns.

### 3.c.2. Normalizing Hourly Loads

The next step in the evaluation involves normalizing the hourly load values by redefining the maximum value from each profile in Figure 2 to unity (maximum value = 1), and then rescaling each profile's remaining values accordingly. Figure 3 illustrates the result. Though perhaps not obvious in Figure 3, the curve with the broadest peak (Load Profile #3) happens to be the plot with the lowest magnitude; that is the profile representing June 22, 1999, in Figure 2. The breadth of the peak demand curve is seen more clearly in Figure 4 which plots the same profiles as those in Figure 3, though it only shows the top 4 percent of the peak load profile.

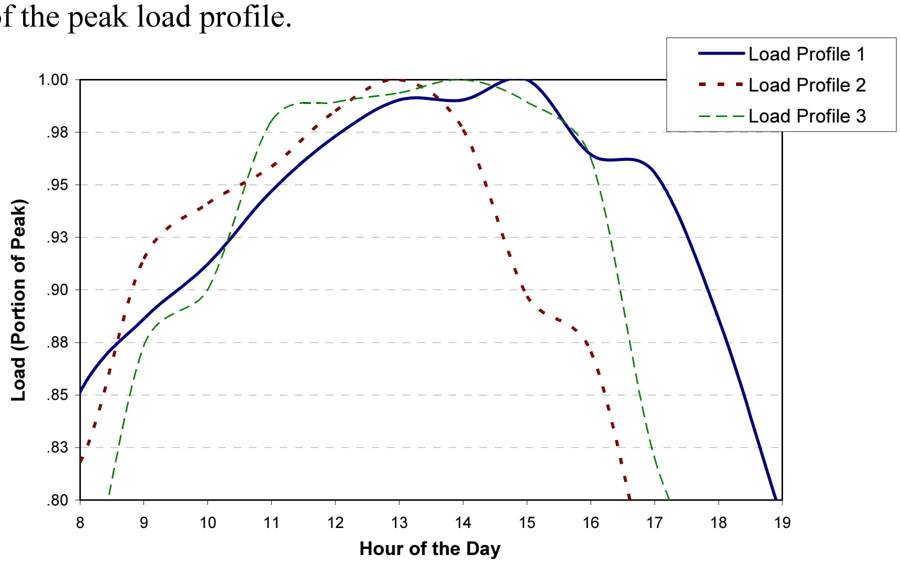


**Figure 3. Normalized Hourly Load Profiles for Three Days with Broad Peaks Shown in Figure 2.**

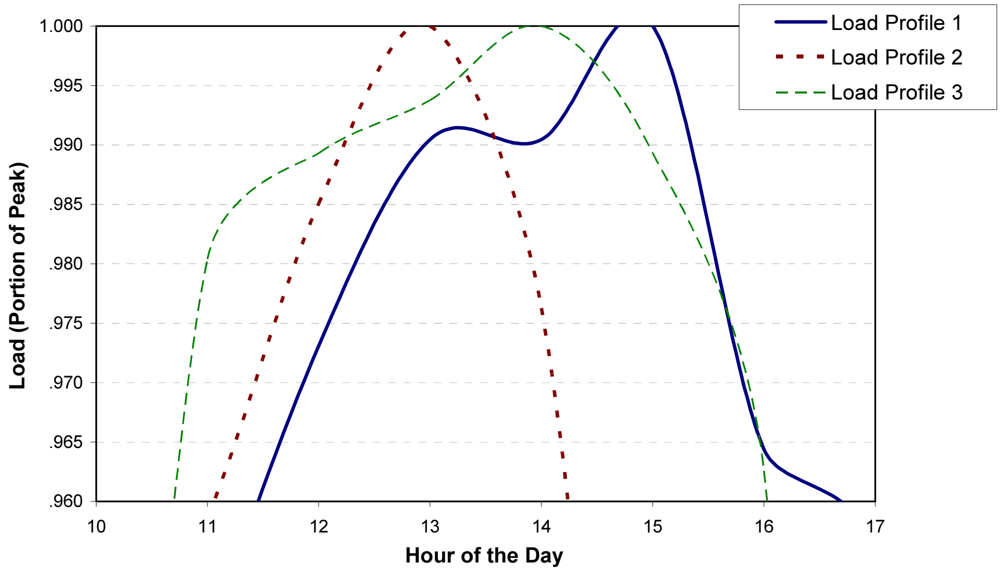


**Figure 4. Top 4% of the Normalized Hourly Load Profiles Shown in Figure 3.**

Based on the example analysis, profile #3 (for 6/22/99) indicates the longest discharge duration (per kW of peak load), and thus the greatest amount of energy needed from storage because that profile has the most area under the curve. If no other profiles are evaluated, then profile # 3 becomes the design load profile.

### *3.d. Discharge Duration Required*

This analysis process involves the use of the design load profile found in Section 3.c. to estimate the storage plant's discharge duration. Examples in this section illustrate the use of load profile #3 as the basis for the design load profile.

The process is shown graphically beginning with Figure 5. That figure has three load plots based on the design load profile: the first plot is the hourly load for the base year, and the second and third plots show hourly loads for two subsequent years after applying a 2% annual load growth rate to the base year values. Also shown is the T&D equipment rating (labeled as "Load Carrying Capacity" in the figure).

The hourly load values reflect the following bases:

- In year 2003, the magnitude of the peak demand was 11.51 MW and it occurred on July 15, 2003. The 11.51 MW is assumed to be the base year peak load.
- The load profile to use–the design load profile–is based on hourly loads that occurred on June 22, 1999. On that day the peak demand was 7.85 MW.
- The hourly loads from June 22, 1999 are adjusted (scaled up) by a factor of 11.51 MW ÷ 7.85 MW = 1.466.

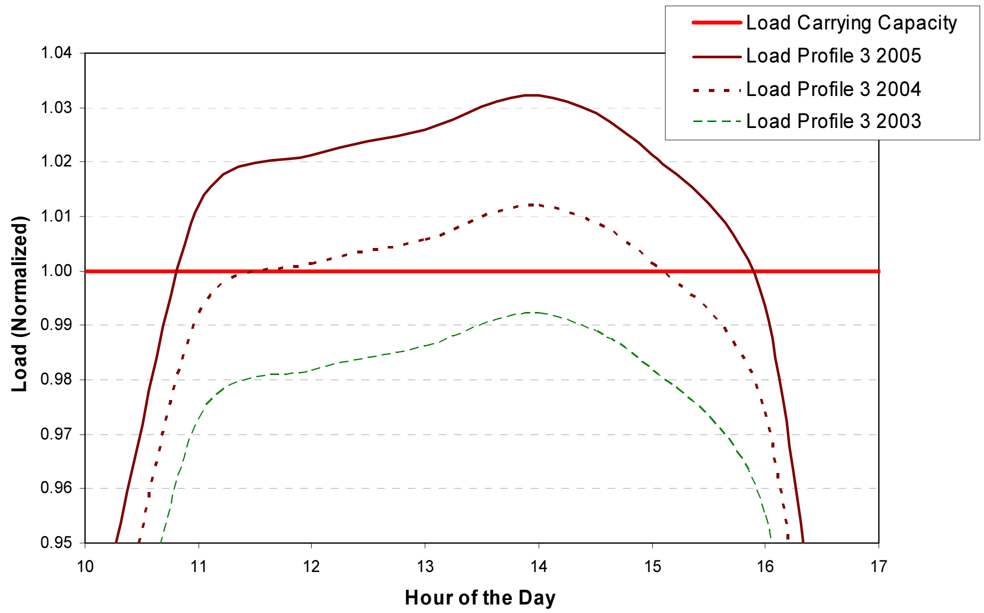


**Figure 5. Load Profile for Base Year and for two Subsequent Years, Reflecting a 2% Annual Load Growth Rate, and after Normalizing to the Annual Peak Load in the Base Year.**

Given the design load profile, calculating the design discharge duration for the storage system involves straightforward mathematic integration of the storage power output over the time during which the storage must discharge (where the power is the amount of *load in excess of the T&D equipment's rating*). Dividing that amount (energy discharged) by the peak power requirement (in excess of the T&D equipment's rating) yields the discharge duration.

In Figure 6, the plot line labeled "Historic Load in 2003" represents hourly loads in 2003 based on the design load profile. The plot line labeled "Projected Load in 2004" represents a projection of hourly loads for 2004 after 2% load growth.

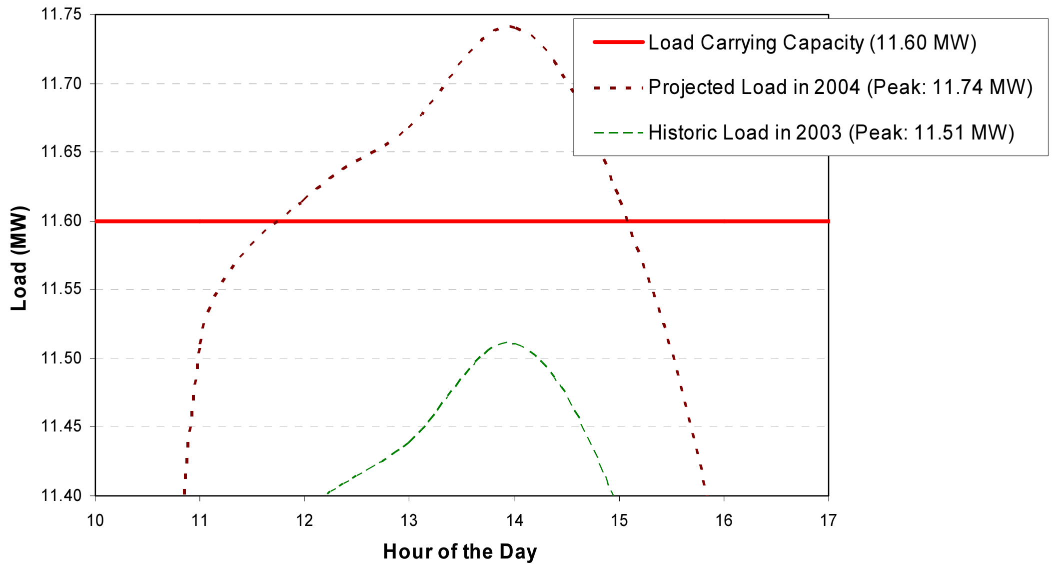


**Figure 6. Load Profiles for Base Year and after One Year of Projected Load Growth.**

As shown in Figure 7, the portion of the load plot for 2004 that is above the line for T&D capacity, labeled "Load Carrying Capacity", indicates the amount of energy needed and, indirectly, the discharge duration. Also indicated is the amount of power needed to serve projected load growth in excess of the load carrying capacity, i.e., about 140 kW in the example (11.74-MW peak – 11.6 MW of distribution equipment load carrying capacity). Table 1 contains the numeric values underlying the profile plotted in Figure 7.

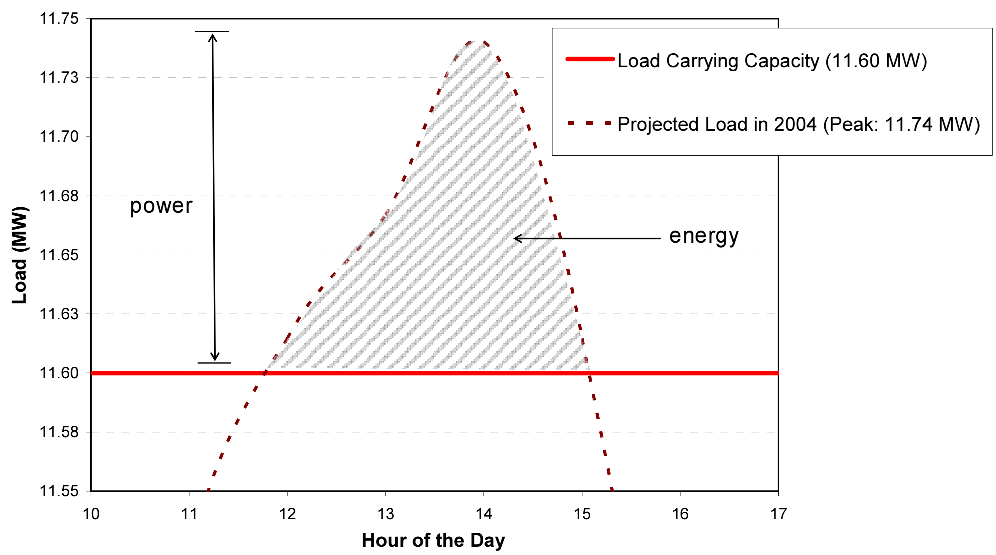


**Figure 7. Hourly Loads for Peak Day After Adding 2% to Reflect Load Growth.**

The design discharge duration is calculated by: a) summing the amount of energy needed if the storage system is to serve load in excess of the T&D equipment's rating, and b) dividing by the projected overload. In the example and from the table, the projected overload is 0.140 MW (140 kW) in 2004.

**Table 1. Hourly Loads (in MW) for Design Load Profile Example for a T&D node with a Nominal Rating of 11.6 MW**

| | Hour of the Day for Design Load Profile | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Year | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 |
| 2004 | 10.57 | 11.51 | 11.61 | 11.67 | 11.74 | 11.61 | 11.30 | 9.63 |

For this example, the result of that calculation is shown in Table 2. Data in Table 2 includes: a) the storage system's power rating, b) the amount of energy that would be delivered to the load from storage given the hourly loads in Table 1, and c) the design discharge duration calculated by dividing the energy needed (MWh) by the storage plant rating (MW).

In the example, when summing the hourly load exceeding the T&D load carrying capacity, the estimated energy required (to meet demand that exceeds the T&D node's rating) is 0.236 MWh. Dividing the power needed (0.140 MW) into that amount of energy yields the discharge duration. In this case 0.236 MWh ÷ 0.140 MW = 1.69 Hours.

**Table 2. Example Estimated Power, Energy and Design Discharge Duration for Year 1 (2004)**

| Year | Power MW | Energy MWh | Discharge Duration (hours) |
|---|---|---|---|
| 2004 | 0.14 | 0.236 | 1.69 |

## *3.e. Other Engineering Considerations*

### 3.e.1. Energy Storage Charging

Until this point, the authors have not discussed charging of the storage system. The amount of time that the storage system requires for charging is the charge duration. Charge duration is a function of discharge duration, storage efficiency, the type of storage technology (chemistry and/or physical characteristics), and the storage system's power electronics rating.

Each storage technology has specific charge characteristics that must be considered in determining the charge duration and other attributes. For example, some batteries can be recharged to approximately 80% of full charge at very high rates (short duration), but then must be charged more slowly to the fully charged condition. Some technologies do not need to be fully charged on every occasion, while others require full charge to avoid degradation. Other technologies can only be charged at a constant, low rate. Finally, some technologies require a complex, carefully controlled charging profile for maximum performance, lifetime or safety. The examples given below assume the simplest case for charging, but the specifics of each technology must be considered in implementing a complete storage system.

In general, it is assumed that charging will occur during off-peak hours, during late night and early morning, when local and regional demand is low, and when electricity use and price are low. It is further assumed that off-peak periods are long enough to charge the storage for the next peak demand period. The key point is that for any specific hot spot it is important to determine whether the location-specific circumstances allow for adequate charging of the specific type of storage used.

Consider an example involving storage that can be charged at a rate that is very similar to the rate at which it is discharged: if the discharge duration is 5 hours and the storage efficiency is 70%, then the charge duration is 5 hours / 70% = 7.1 hours.

### 3.e.2. Resolution of Load Data

The examples shown above involved use of hourly load data. If higher resolution data is available, then that may be used for a more precise result.

### 3.e.3. Refining the Result

Getting a more refined result will require some engineering judgment. The discharge duration estimation exercise described above is intended to provide a conservative result. That is, assuming that a worst case load profile can be defined with a high degree of certainty, then using that profile yields a storage system discharge duration which should be adequate for most scenarios.

Of course, it is unlikely that the analysts can be so certain; hence the need to exercise engineering judgment and to accommodate uncertainty and knowledge gaps. The resulting manifestation, with respect to the storage system, will likely be a discharge duration that is longer than that estimated from the load profiles as described in this section.

The most conservative approach is to design the storage system so it can provide full output during all hours when peak demand is expected to exceed the T&D capacity.

# Section 4. Multi-Year Deferrals

Storage power and discharge duration values, developed as described in Sections 2 and 3, respectively, yield values that apply to one specific year. If storage is to be used for more than one year at the same location, then the same storage sizing evaluation (power and discharge duration) must be repeated for each subsequent year.

## *4.a. Storage Power Rating*

Estimating the storage power rating for a subsequent year is straightforward (for a specific estimate of load growth).

For each additional year that storage is expected to be used for the same deferral, the base case design load (for the respective year) is equal to the design load for the first year plus all load growth in subsequent years.

Consider the example provided in Table 2: in year 1, after 2% growth, the load exceeds the T&D rated capacity by 140 kW so the design load for that year is 140 kW. In year 2, after two years of load growth at a 2% annual rate, load exceeds the T&D capacity by 375 kW.

So, if storage is to be used at that location in year 2, then the design load for that year is 375 kW: 140-kW design load in year 1, plus an amount equal to another 2% load growth in year 2 (235 kW).

Note that the 235 kW of power needed in year 2 is nearly twice the amount installed in year 1. This is shown graphically in Figure 8.

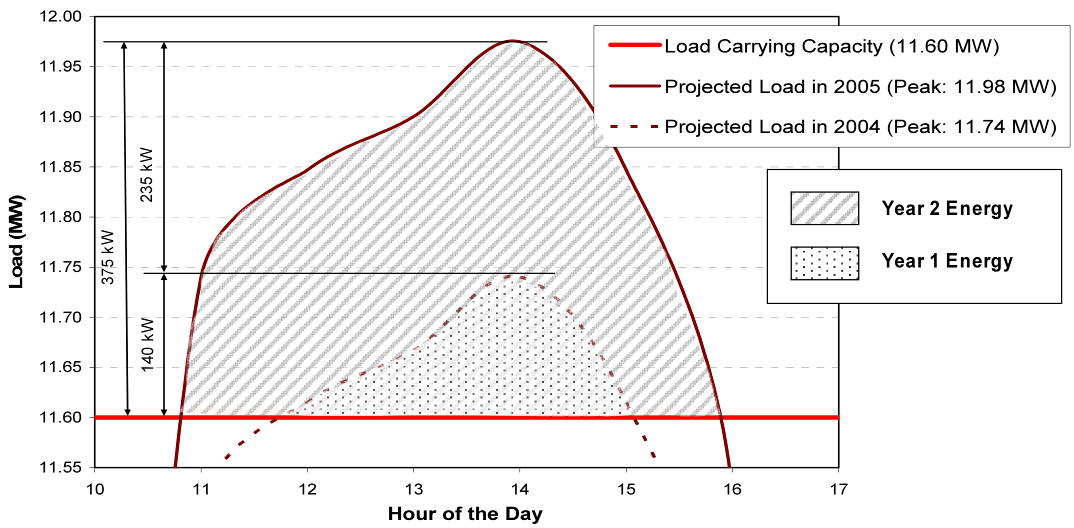


**Figure 8. Storage Power and Energy Requirements for Two Years of T&D Upgrade Deferral.**

## *4.b. Storage Discharge Duration*

In addition to increasing the storage system's power rating for subsequent years of deferral, in most cases the discharge duration must also be increased. As seen in Figure 8, the discharge duration is represented by the area under the power vs. time curve.

Consider again the example provided in Table 2: in year 1, the design discharge duration is 1.69 hours. When doing the analysis described in Section 3 for a possible deferral in year 2, the estimated discharge duration is 3.49 hours. This is also shown in Figure 8.

Data used to create Figure 8 are shown in Table 3 and Table 4. Table 3 contains numeric values underlying the profiles plotted in Figure 8. Table 4 contains results from the storage sizing exercise undertaken for years 1 and 2 for the example.

**Table 3. Hourly Loads (in MW) for Design Load Profiles for Years 1 and 2 (2004 and 2005)**

| | Hour of the Day for Design Load Profile | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Year | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 |
| 2005 | 10.78 | 11.74 | 11.85 | 11.90 | 11.98 | 11.85 | 11.53 | 9.82 |
| 2004 | 10.57 | 11.51 | 11.61 | 11.67 | 11.74 | 11.61 | 11.30 | 9.63 |

**Table 4. Example Estimated Load, Energy, and Discharge Durations for Years 1 and 2 (2004 and 2005)**

| Year | Power MW | Energy MWh | Discharge Duration (hours) |
|---|---|---|---|
| 2005 | 0.235 | 1.07 | 3.49 |
| 2004 | 0.14 | 0.236 | 1.69 |

# Section 5. Identifying Favorable Sites for Storage as T&D Capacity Deferral

This section provides a brief characterization of criteria to consider when screening possible projects/locations for which modular storage systems could be a cost-competitive alternative to a T&D upgrade.

## *5.a. Criteria for Identifying Candidate Hot Spots*

Presumably all or almost all projects/locations for which DES may be an attractive option will have been identified as hot spots during the normal T&D planning cycle. The next step is to identify candidate hot spots for which DES may be the lowest cost option to serve peak load on the margin.

Modular DERs, including DES, are most likely to be viable options for situations characterized by some combination of the following (in no particular order):

- load growth will only exceed the T&D system's rating by a small portion (i.e., projected overload will be relatively small);
- peak load is growing at a slow rate;
- high maximum load to average load ratio, during times when peak load occurs; such locations are sometimes said to have a "peaky" maximum load profile;
- the upgrade has a high unit cost (i.e., on a $/kVA of capacity-added basis); includes both direct and "soft" costs such as good will and reputation;
- the T&D upgrade project competes with other important projects for capital;
- uncertainty regarding the timing and/or likelihood of block load additions;
- T&D construction delays or construction resource constraints may be a challenge.

DES is especially well suited to those locations if:

- the same storage capacity provides additional benefits which can be combined with T&D deferral-related benefits, to comprise an attractive total value proposition (e.g., add benefits from improved power quality and/or reliability, plus the value of on-peak energy, plus benefits from reduced loading on the transmission system);
- air emissions regulations, noise regulations, fuel storage or other safety-related challenges restrict use of distributed generation.

## 5.b. Locations with Limited Projected Overload

Generally DES and other DERs are more attractive for situations involving relatively small projected overloads. That is because a relatively small amount (kW) of DES or DER is needed to serve peak load on the margin.

### 5.b.1. T&D Capacity Slack

A key basis for projected overload is the difference between the maximum demand during the previous year and the load carrying capacity (rating) of the T&D equipment serving that load, i.e., capacity slack. Capacity slack varies among hot spots. This concept is shown graphically in Figure 9.

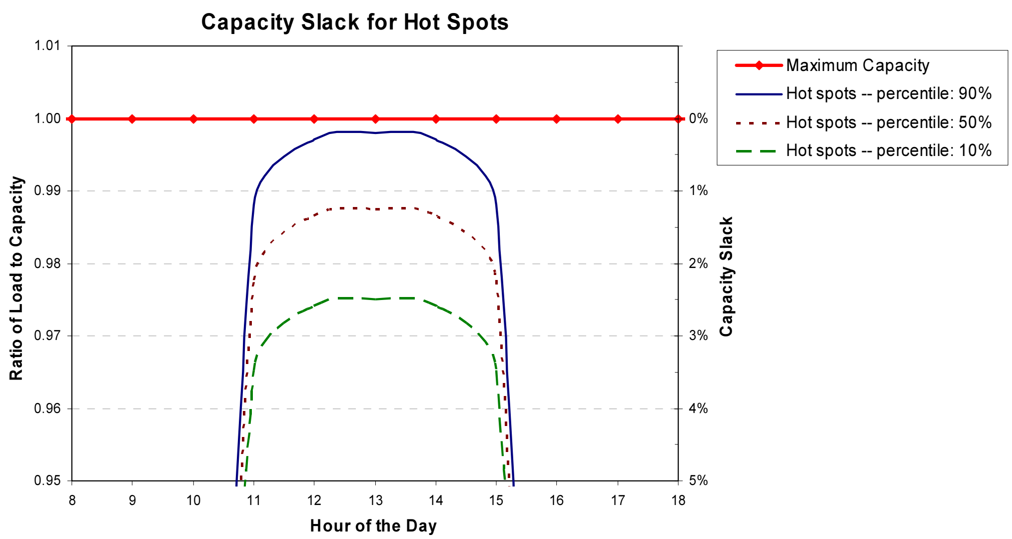


**Figure 9. Variability of T&D Loading Relative to T&D Rating, Among Hot Spots.**

Consider as an example two very similar distribution system hot spots with a rated capacity of 12,000 kW and in this case, a 3% annual load growth. In both locations, the upgrade will involve adding 4,000 kW. The upgrades will cost $1,040,000 each ($260/kW of T&D capacity added), or about $135,000 per year (assuming a fixed charge rate of 0.13 to calculate the annual carrying cost for the initial investment).

At the first location, peak loading in the base year is about 98% of the equipment's rated capacity. If load grows by the expected 3% then the projected overload is about 1% in the next year. That is an expected overload of 12,000 kW of existing capacity * 1% = 120 kW.

At the second location, the previous year's peak load was almost the same as the T&D equipment's rated capacity. In that case, if load growth is 3%, then the next year's projected overload is nearly 360 kW (12,000 kW * 3%).

At the first location, the storage system's benefit is about $135,000 ÷ 120 kW = $1,125/kW of storage (for one year of deferral).  At the second location, the storage system's benefit for one year of deferral is about $135,000 ÷ 360 kW (0.3 MW) = $375/kW of storage. This relationship is illustrated in Figure 10.

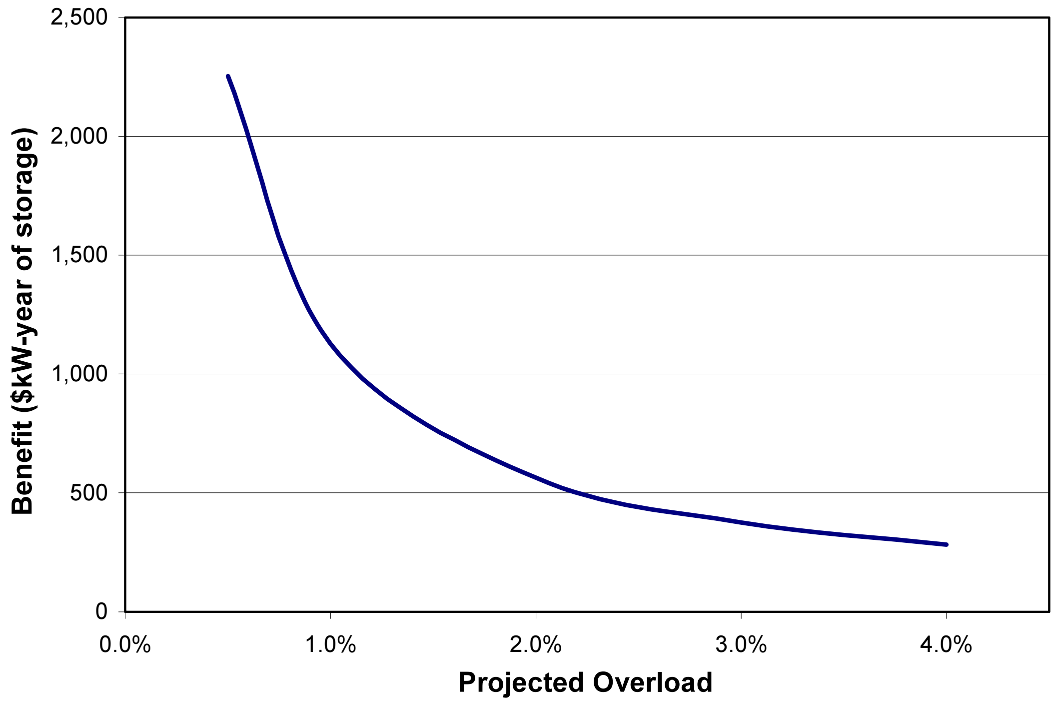


**Figure 10.  One-year Deferral Benefit from Modular Storage as Function of Projected Overload.**

## *5.c. Locations with High Peak to Average Load Ratios*

DERs and DESs are especially well suited to locations where peak loading has a relatively short duration. Those are locations with a peak to average load ratio that is relatively high. Such locations are sometimes said to have "peaky" load profiles.

The plots in Figure 4 illustrate this characteristic. Profile #2 is the narrowest and most peaky, while the profile with the broadest, least peaky maximum is profile #3.

DESs serving such locations require the least amount of energy (stored) per kW of peak demand served. For DES that means shorter discharge duration and for DGs that implies less fuel storage, use, and pollution.

### 5.d. Locations with Uncertain Load Growth

Generally DES and other DERs are more attractive when peak load growth is uncertain. Though there may be uncertainty about the core rate of load growth; modular DES may help most when there is uncertainty about the magnitude and timing of block load additions.

This may be especially compelling for situations involving uncertainty about availability of resources (e.g., land availability and/or capital) needed for the upgrade. Regulatory requirements, such as industrial permitting (e.g., building, electrical, and fire code permits) and other types of approvals, also create uncertainty.

## Section 6. Results and Conclusions

### 6.a. Summary and Key Conclusions

This report describes a fairly straightforward process to evaluate the power output and discharge duration capacities for modular energy storage systems that may be used to defer utility T&D upgrades. Analyzing the merits of using energy storage for T&D deferral requires a combination of: a) standard distribution system data, methodologies, tools, and rules; b) historic diurnal load profiles representing possible hourly load profiles during the season/days when maximum demand occurs or standard load profiles used in T&D capacity planning; c) normal engineering judgment; and d) the evaluation steps described in this document.

Ideally, this methodology could be easily integrated into initial or screening level evaluations undertaken for traditional T&D planning. Though it adds a few additional steps and facets to standard T&D planning, storage system sizing for T&D upgrade deferral requires much of the same data, depends on many of the same criteria, and involves similar techniques and concepts as conventional T&D capacity planning. As energy storage becomes more widely used, we expect the methodology, or a similar one, to become more common.

In general terms, using storage systems that have: a) power ratings ranging from 1% to 4% of the local T&D peak load; and b) discharge durations of two to five hours may be a technically viable way to defer T&D upgrades.

If the annualized cost to own and to operate modular energy storage is less than the annualized cost for a T&D upgrade, then the storage option may be the lowest cost to ratepayers and may even be the lowest risk option to stockholders.

In addition to reducing total cost (of service) to utility ratepayers, use of storage may allow distribution planners to serve more peak load with the same total budget. Depending on circumstances, this may involve capital and/or expense budgets.

## *6.b. R&D Needs, Opportunities, and Next Steps*

The sizing process described is quite adequate for screening-level evaluations. However, the authors presume that T&D planners may need a more formalized methodology that is appropriately vetted (e.g., by the Institute of Electrical and Electronics Engineers (IEEE) or by relevant utility regulatory agencies) before widespread adoption. An important next step is to identify and begin the process of such vetting. Regulators and IEEE Standards Committees should be consulted to establish a proposed protocol for vetting this methodology.

Transmission and distribution planners and engineers rarely have the authority, tools, or familiarity required to consider unconventional ways to serve T&D capacity needs on the margin as described in this report. An important way to address that situation is to provide T&D planning and engineering stakeholders with opportunities to learn more about how storage increases T&D planning options and flexibility, and how it may reduce utility cost of service, including risk.

A low-cost and low-risk next step is for knowledgeable T&D engineers to "try and apply" the sizing process described in this report without actually installing storage. In fact, the process could be applied to historic cases. T&D engineers could use the sizing process to estimate storage power and discharge duration required for specific cases. Then, actual peak loading for the "next" year would be evaluated to determine whether storage would have provided the expected benefit. The lessons learned would then be compiled, synthesized, and published.

Based on: 1) reviews for vetting, and 2) results from the try-and-apply exercise, the sizing methodology would be refined to address technical issues associated with the evaluation. The result would be a process with more specific "hooks" needed to integrate the methodology into standard T&D planning. If indicated, simple computer tools could be developed to streamline the calculations.

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## Definitions

***Base Year***–the year preceding the year in which a T&D upgrade is expected, also referred to as Year 0.

***Base Year Peak Load***–The maximum load during the year before the T&D upgrade is needed.

***Damping***–Decrease in the amplitude of an oscillation or wave motion with time.

***Charge Duration***–The amount of time needed to charge a storage plant so it can operate at rated output for a specific *Discharge Duration*. Charge Duration is a function of *Discharge Duration, Storage Technology,* and *Storage Efficiency*.

***Design Discharge Duration***–the *Discharge Duration* (in units of time) required if storage will serve utility load at a specific T&D node.

***Design Load***–the amount of load (kW or MW) which must be served by storage. Design Load is normally a function of *Projected Overload*.

***Design Load Profile***–hourly loads, in chronological order, representing a day when both demand is at its maximum and when the hourly demand profile is broadest.

***Design Relative Humidity***–Ambient relative humidity (%) assumed for a T&D design. It is the highest relative humidity "expected" when peak demand occurs. Examples are worst case, one-year-in-ten, or one-year-in-one-hundred.

***Design Temperature***–Ambient temperature assumed for a T&D design. It is the highest temperature "expected" when peak demand occurs. Examples are worst case, one-year-in-ten, or one-year-in-one-hundred.

***Discharge Duration***–for an energy storage system, the amount of time (seconds, minutes, or hours) that the system must be able to discharge, at the *Storage Power Rating*, without recharging.

***Discharge Energy***–for an energy storage system, the amount of electric energy discharged (kWh, MWh) if the storage system discharges continuously at the *Storage Power Rating* for the *Discharge Duration*.

***Expected Value***–In this document, the term "expected" implies a likelihood–based on statistical criteria–rather than an actual expectation. For example, "expected maximum temperature" is not the temperature that we actually think will prevail at a specific time on a certain day; instead it is the maximum to use for design. Expected maximum temperature is derived given statistical data such as one-year-in-ten (based on historic data).

***Hot Spot***–see *T&D Hot Spot*.

***Projected Overload***–for a *T&D Hot Spot*, the portion of the projected electric demand which will exceed the load carrying capacity in a specific year. Units are expressed in kW or MW. Example: if load is 9.85 MW at a *T&D Hot Spot* with a rating of 10 MW and load growth is projected to be 3%, then the projected overload is (9,850 kW * 3%) - 10,000kW = 145 kW.

***Storage Efficiency***–The amount of energy output from an energy storage system for each unit of energy input; also referred to as round trip efficiency. Typical values are 70% to 80%.

***Storage Power Rating***–Maximum power that the storage system must provide. When sizing a storage plant for T&D deferral, this value should equal to *Design Load*. (Note that some storage systems can provide additional power–in excess of the plant's "nominal" rating–for short periods of time.)

***T&D Emergency Rating***–Maximum power that the T&D system can provide, at the T&D node of interest, for short periods of time, under "emergency" conditions. It is rare to operate T&D equipment at this power level.

***T&D Hot Spot***–a T&D node that does or will soon require an upgrade due to one or more of the following: 1) heavy peak loading that is at or near the equipment's load carrying capacity, 2) equipment damage, 3) equipment's age has or will soon exceed its useful life, or 4) unacceptable local power quality or reliability.

***T&D Nominal Rating***–Maximum power that the T&D system can provide (under specified conditions), at the T&D node of interest, as specified by the equipment nameplate or other acceptable rating (i.e., for conductors). Normally, equipment is not operated such that power exceeds this rating.

***T&D Rating***–Maximum power that the T&D system can provide for given design criteria such as ambient temperature. It is the assumed maximum load carrying capacity of the T&D equipment for a specific scenario/case. In any specific scenario/case, it may be the *T&D Nominal Rating* or the *T&D Emergency Rating*.

***Year 1***–the year in which there is an expected need for a T&D upgrade, one year after the *Base Year*.

***Year 2***–the second year in which a T&D upgrade may be needed, two years after the *Base Year*.

# Appendix A.
## Distribution Cost and Deferral Value Example Worksheet

Values in the worksheet below reflect the costs for an example distribution upgrade. The annual cost of $34/kW-year is at the low end of the cost spectrum for California.[5] Likewise, the installed cost of $260/kW is at the low end of the spectrum. [6][7][9]

### Distribution Existing Capacity and Load

| | | |
|---|---|---|
| Equipment Maximum Capacity (kW) | 12,000 | equipment "nameplate" rating |
| Peak Load, Current Year (kW) | 12,000 | peak load = equipment rating in year before upgrade |

### Distribution Capacity Added

| | | |
|---|---|---|
| Capacity *Added* (kW) | 4,000 | + 33% |
| Addition "Life" (Years before next upgrade) | 11.7 | based on 2.5% annual average load growth rate |

### Distribution Equipment Cost

| | | |
|---|---|---|
| Equipment Cost ($/$kW_{nameplate}$) | 35 | transformers, wires, etc. |
| Installation Cost ($/$kW_{nameplate}$) | 30 | mostly labor, permitting and other "compliance," G&A overheads |

### Distribution Project Cost

| | | |
|---|---|---|
| Equipment Installed Cost ($/kW) | 65 | $35/kW equipment + $30/kW installation |
| Upgraded Equipment Capacity (kW) | 16,000 | 12,000 kW existing + 4,000 kW added |
| Total Installed Cost ($) | 1,040,000 | 16,000 kW total * $65/kW |
| Annualization Factor, for Financing* | 0.13 | used to calculate annual cost (carrying charges) for upgrade |
| Annual Upgrade Ownership Cost ($) | 135,200 | $1,040,000 * 0.130 annualization factor |

### Distribution Capacity Marginal Cost

| | | |
|---|---|---|
| Installed Cost ($/kW *added)* | 260 | $1,040,000 total installed cost / 4,000 kW added |
| Annual Cost ($/kW-year *added)* | 34 | $260/kW installed cost * 0.130 annualization factor |

### Load Projection

| | | |
|---|---|---|
| Projected Load Growth (% next year) | 2.5% | annual average |
| Peak Load Growth "Next Year" (kW) | 300 | 12,000 kW * 2.5% |
| Load Exceeding Maximum (kW)** | 300 | 7.5% of 4,000 kW upgrade |
| Ratio: Upgrade Capacity/Load Growth | 13.3 : 1 | 4,000 kW added / 300 kW exceeding existing capacity |

### Upgrade Deferral Value

| | | |
|---|---|---|
| Capacity Needed "on the margin" (kW) | 300 | load in excess of existing equipment capacity |
| DER Capacity Oversizing | 0% | engineering contingency |
| DER Capacity (kW) | 300 | |

| **One time, single year benefit** | **$/kW** | **¢/Watt** | |
|---|---|---|---|
| **for adding 300 kW of capacity or for reducing load by 300 kW** | **451** | **45.07** | $135,200 annual cost / 300 kW storage |

*Accounts for annual interest, dividend, depreciation, tax, and insurance payments.

**The portion of load that exceeds the existing equipment's maximum capacity of 12,000 kW.

# Distribution

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

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

Brad Johnson
2122 Natahoa Court
Falls Church, VA  22043

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

Robert D. Weaver
12327 Dry Creek Road
Auburn, CA  95602-9339

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

Warren Ziegler
Acumentrics Corporation
20 Southwest Park
Westwood, MA  02090

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

David Nichols
AEP
4001 Bixby Road
Groveport, OH  43125

Donald A. Bender
AFS Trinity Power
6724D Preston Avenue
Livermore, CA  94550

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

Paul Grems Duncan
Airak, Inc.
21641 Beaumeade Circle, Ste. 300
Ashburn, VA 20147

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

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

David Lockard
Alaska Energy Authority/AIDEA
813 West Northern Lights Boulevard
Anchorage, AK 99503

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

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

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

Richard Baxter
Ardour Capital Investments, LLC
127 Mt. Auburn St., Suite 17
Cambridge, MA 02138

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

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

Ray Hobbs
Arizona Public Service
400 North 5th Street
P.O. Box 5399, MS8931
Phoenix, AZ 85072-3999

William Capp
Beacon Power
234 Ballardvale Street
Wilmington, MA 01887

Matthew Lazarewicz
Beacon Power Corporation
234 Ballardvale Steet
Wilmington, MA 01887

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

Gerry Woolf
BEST Magazine
17 West Meston Ave
Rottingdean, East Sussex BN2 8AL
UNITED KINGDOM

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

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

Michael Hoffman
Bonneville Power Administration
P.O. Box 3621, 'Mail Stop: PND-1
Portland, OR 97208-3621

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

Septimus van der Linden
BRULIN Associates, LLC.
14418 Old Bond Street
Chesterfield, VA  23832

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

Pramod Kulkarni
California Energy Commission
PIER Storage Program
1516 9th Street, MS 43
Sacramento, CA  95758

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

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

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

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

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

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

Sn Horgan
Distributed Utility Associates Inc.
1062 Concannon Blvd.
Livermore, CA  94550

Ben Norris
Distributed Utility Associates Inc.
1062 Concannon Blvd.
Livermore, CA 94550

Rick Winter
Distributed Utility Associates Inc.
42 Ardilla Rd
Orinda, CA 94563

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

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

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

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

Alfred Rufer
Ecole Polytechnique Federale de Lanne (EPFL)
STI - LEI, Station 11
Lanne, VD CH1015
SWITZERLAND

K.M. Abraham
E-KEM Sciences
P.O. Box 920401
Needham, MA 02492

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

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

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

Steve Eckroad
Electric Power Research Institute
1300 West WT Harris Blvd.
Charlotte, NC  28262

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

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

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

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

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

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

Edward Skolnik
Energetics A Subsidiary of VSE Corporation
901 D Street SW, Suite 100
Washington, DC  20024

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

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

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

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

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

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

Ed Beardsworth
Energy Technology Advisors
951 Lincoln Avenue
Palo Alto, CA 94301

R. B. Sloan
Energy United
PO Box 1831
Statesville, NC 28687

Sanjay Deshpande
EnerSys Inc
2366 Bernville Road
Reading, PA 19605

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

Robert Schainker
EPRI
3412 Hillview Ave
P.O. Box 10412
Palo Alto, CA 94304-1395

Haresh Kamath
EPRI Solutions
942 Corridor Park Blvd
Knoxville, TN 37909

Tom Key
EPRI Solutions
942 Corridor Park Blvd.
Knoxville, TN 37932

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

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

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

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

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

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

Robert Schmitt
GNB Industrial Power
3950 Sussex Avenue
Aurora, IL 60504

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

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

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

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

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

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

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

André Bélanger
Institut de recherche d'Hydro-Quebec
1800 Boul. Lionel Boulet
Varennes, Quebec J3x 1S1
CANADA

Fred Schwartz
Intellergy
595 Whitewood Drive
San Rafael, CA 94903

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

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

Patrick Moseley
International Lead Zinc Research Org., Inc.
2525 Meridian Parkway
Research Triangle Park, NC  27516

Carl Parker
International Lead Zinc Research Org., Inc.
P.O. Box 12036, Research Triangle Park
Durham, NC  27709

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

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

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

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

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

Dutch Achenbach
Kauai Island Utility Cooperative
4463 Pahe'e Street, Suite 202
Lihue
Kauai, HI  96766

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

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

Jim Fiske
Launchpoint Technologies
5735-B Hollister Ave.
Goleta, CA  93117-3420

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

Chris Marnay
Lawrence Berkeley National Laboratory
1 Cyclotron Road, MS 90-4000
Berkeley, CA  94720

Frank R. McLarnon
Lawrence Berkeley National Laboratory
1 Cyclotron Road
Berkeley, CA  94720

J. Ray Smith
Lawrence Livermore National Laboratory
7000 East Avenue
P.O. Box 808
Livermore, CA  94551

Susan Schoenung
Longitude 122 West, Inc.
1010 Doyle Street, Suite 10
Menlo Park, CA  94015

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

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

Lumas Kendrick
McNeil Technologies
6564 Loisdale Court, Suite 900
Springfield, VA  22150

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

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

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

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

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

Amit Singhal
NEI Corporation
201 Circle Drive, Suite 102/103
Piscataway, NJ  08854

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

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

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

Toyoo Takayama
NGK Insulators, Ltd.
2-56 Suda-cho, Mizuho
Nagoya,  467-8530
JAPAN

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

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

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

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

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

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

Salah Oweis
OWEITECH
4705 Hallowed Stream
Ellicott City, MD  21042

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

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

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

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

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

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

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

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

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

Brad Roberts
S&C Electric Company
5251 West Franklin Drive
Franklin, WI 53132

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

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

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

Mindi Farber de Anda
SAIC
8301 Greensboro Dr. M/S E-5-7
McLean, VA 22102

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

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

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

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

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

Anthony Price
Swanbarton Limited
Barton House, Swan Barton
Sherston, Malmesbury SN16 OLJ
UNITED KINGDOM

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

Harold Gotschall
Technology Insights
6540 Lusk Blvd, Ste C-102
San Diego, CA 92121

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Philip N. Overholt
U.S. Department of Energy
1000 Independence Avenue, SW
Rm. 6H-024, TD-2
Washington, DC 20585-0121

William P. Parks Jr
U.S. Department of Energy
1000 Independence Avenue, SW, OE-10, FORS
Washington, DC 20585

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

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

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

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

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

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

Mariesa Crow
University of Missouri-Rolla
305 McNutt Hall
Rolla, MO 65409

John Herbst
University of Texas
1 University Stations R7000
Austin, TX 78712

Bob Lasseter
University of Wisconsin
1415 Engineering Dr.
Madison, WI  53706

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

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

Mark Kuntz
VRB Power Systems Inc.
1645 - 701 W. Georgia St.
Vancouver, BC  V7Y 1C6
CANADA

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

Rusi Patel
Xenergy/KEMA consulting
3 Burlington Woods
Burlington, MA  01803

Yoshiyasu Yamamoto
YC Consulting
6102 Shelby Street
Indianapolis, IN  46227

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

Robert Parry
ZBB Energy Corporation
N93W14475 Whittaker Way
Menomonee Falls, WI  53051

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

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

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

| | |
|---|---|
| MS0511/01010 | Wendy Cieslak |
| MS0512/02500 | Thomas E. Blejwas |
| MS0613/02520 | Robert W. Bickes, Jr. |
| MS0613/02520 | Michael Prairie |
| MS0613/02521 | Daniel H. Doughty |
| MS0614/02522 | Stanley Atcitty |
| MS0614/02522 | Nancy Clark |
| MS0614/02522 | Thomas Hund |
| MS0614/02523 | Rudolph G. Jungst |
| MS0614/05400 | Paul C. Butler (10) |
| MS0710/06251 | John Boyes (5) |
| MS0710/06251 | Garth Corey |
| MS0710/06251 | John W. Stevens |
| MS0741/06200 | Marjorie L. Tatro |
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