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THE MARKET POTENTIAL FOR SMES IN ELECTRIC UTILITY APPLICATIONS

FINAL REPORT

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Abstract

Superconducting magnetic energy storage (SMES) is an emerging technology with features that are potentially attractive in electric utility applications. This study evaluates the potential for SMES technology in the generation, transmission, distribution, and use of electric energy; the time frame of the assessment is through the year 2030. Comparisons are made with other technology options, including both commercially available and advanced systems such as various peaking generation technologies, transmission stability improvement technologies, and power quality enhancement devices. The methodology used for this study focused on the needs of the market place, the capabilities of SMES, and the characteristics of the competing technologies.

There is widespread interest within utilities for the development of SMES technology, but there is no general consensus regarding the most attractive size. Considerable uncertainty exists regarding the eventual costs and benefits of commercial SMES systems, but general trends have been developed based on current industry knowledge. Results of this analysis indicate that as storage capacity increases, cost increases at a rate faster than benefits. Transmission system applications requiring dynamic storage appear to have the most attractive economies. Customer service applications may be economic in the near term, but improved ride-through capability of end-use equipment may limit the size of this market over time. Other applications requiring greater storage capacity appear to be only marginally economic at best.

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1.0 Summary

1.1 Introduction

Superconducting magnetic energy storage (SMES) is an emerging technology with features that are potentially attractive in electric utility applications. SMES is based on the concept of storing energy in the magnetic field produced by a direct current (DC) flowing in a superconducting coil. Electrical energy is transferred into and out of the coil through solid state power conversion equipment.

SMES applications have been proposed in all four segments of the electric utility industry: generation, transmission, distribution, and customer service. The applications can be defined by the size of the application, and the relative amounts of power capacity (measured in megawatts - MW) and storage capacity (measured in megawatt hours - MWh) needed. These applications cover an extremely wide range of power capacity and storage requirements (see Exhibit 1-1).

Exhibit 1-1 Typical Proposed Electric Utility SMES Applications

SMES has a number of features which make it potentially attractive for electric utility applications. These include extremely rapid charge/discharge rates, high storage efficiency, and very long lifetime (as measured by number of charging cycles). Benefits from the variety of applications which have been suggested for SMES include improving voltage stability, voltage regulation, transmission line deferral, improved system reliability, loss reduction, and reducing the need for reactive power regulating facility requirements. SMES also has benefits for distribution system applications, such as improving power supply reliability, load leveling, and reducing reactive power regulating facility requirements. Finally,

SMES has benefits for end-users of electricity by enhancing power quality and resolving most common power quality problems.

SMES systems have been extensively studied since the 1960s. Small-scale SMES devices (1 MW/1 MW-sec) are in limited commercial demonstration for power quality applications. The largest SMES built to date is the 10 MW/30 MW-sec "Tacoma SMES" constructed in 1983. For utility applications, SMES units as large as 1000 MW/10,000 MWh have been proposed (e.g. for diurnal storage).

Scale-up to large earth-supported SMES systems, such as those proposed for large utility applications, will entail substantial effort, investment, and risk. The Defense Nuclear Agency (DNA) has been supporting SMES development. DNA is currently evaluating, in coordination with the U.S. Department of Energy (DOE), potential opportunities for SMES in civilian applications. The potential technological competitiveness of SMES in various potential markets is being evaluated as input to the DNA/DOE decision on the nature, role, and extent of commercialization support for SMES.

The background to this project and SMES technology is discussed in more detail in Section 2 of the Report.

1.2 Study Objectives

The purpose of this joint DNA/DOE project was to investigate the applications, market potential, and benefit/cost for SMES in the generation, transmission, distribution, and use of electric energy. The study evaluated the market potential for SMES technology in comparison with other technology options, including both commercially available and advanced systems such as various peaking generation technologies, transmission stability improvement technologies, and power quality enhancement devices.

The project had two basic objectives:

- Determine the characteristics of the market segments for "storage" of electric energy in both utility and customer applications, i.e., what size and operating characteristics are required for each expected application.
- Identify those technical, economic, and market benefits which SMES technology may have relative to existing electric energy "storage" options, and advanced "storage" options.

These objectives were supported through additional methodology development and data acquisition objectives.

1.3 Methodological Issues

Evaluating the potential of a developing technology such as SMES poses an interesting methodological challenge. On the one hand, many of the characteristics of SMES and the competing technologies are still uncertain in terms of both the likely cost and the likely performance of the fully commercialized technologies. At the same time, the utility problems amenable to a SMES solution have significant variability in the value (or benefit) of solving the problem. In addition to site-to-site and utility-to-utility variation in benefits, the range of benefit values is likely to change with time, as a utility's power system develops.

Realizing the limitations of a traditional market analysis approach given this uncertainty, a product development approach was used instead. This approach focuses on the needs of the marketplace, the capabilities of SMES, and the characteristics of the competing technologies. These three forces are evaluated to identify those applications where SMES might have a potential competitive advantage to fill the needs of the market better than competing technologies. Ultimately, to be successful, SMES must be both economically attractive in an application and provide performance/cost advantages as compared to the competing technologies.

The approach is discussed in more detail in Section 3 of the Report.

1.4 SMES Background

SMES comprises two technology components, power conditioning and energy storage. The energy storage component serves the same function of storing electricity as other competing storage technologies (e.g., flywheels, batteries, pumped hydro). The power conditioning system transfers power into and out of the storage component and also controls the characteristics (quality) of the power provided to the application. The power conditioning component is not unique to SMES and aspects of the technology can be applied to power conditioning for other storage technologies as well.

Forces exerted by the magnetic field in SMES systems larger than about 1 MWh of storage capacity require the use of significant support structures. SMES systems with energy storage capacity greater than about 20-50 MWh typically are designed to integrate the support structure into the ground. These systems are supported with struts or straps which contact the ground and are typically referred to as "warm supported" because the support is in contact with the warm earth near the cryostat. SMES systems with storage capacity of less than about 20 MWh can utilize free-standing structural steel supports because of smaller forces. These structures typically utilize hoop designs which directly contact the cold cryostat and are referred to as "cold supported."

SMES systems can be designed either with solenoid or toroidal coils. The solenoid coil design uses less superconducting material per unit energy stored and material costs are approximately one-third or less than that of the toroidal coil designs. For

SMES systems requiring hours of storage capacity, solenoid designs are favored in order to reduce material costs. The SMES-ETM is a solenoid design. Solenoid coils have been the focus of most of the development work in the U.S. However, toroidal coils produce a much smaller electro-magnetic field than solenoid coils and are favored by some project developers, especially outside the U.S.

Small cold-supported SMES devices (1 MW/1 MW-sec) are in limited commercial production. A modest 10 MW/30 MW-sec cold-supported SMES experimental unit was built in the early 1980s at Bonneville Power Administration (BPA). No earth-supported SMES device has been built to date and costs for commercial units are uncertain. A 400 MW/20 MWh ground-supported engineering test model (SMES-ETM) has been proposed as the next step in the development of large ground-supported SMES units, such as those proposed for electric utility diurnal storage applications.

SMES capital costs are determined by the rated power capacity (MW) and the storage capacity (MWh) of the unit. For a high power-to-energy ratio, say 1000 MW/1000 MW-sec, the cost of the energy storage system accounts for about 25% of capital cost. As storage capacity increases, storage costs increase rapidly, up to about 80% of total capital costs for large (1000 MW/10,000 MWh) SMES systems.

1.5 Summary of Results

Exhibit 1-2 displays the relative economic attractiveness of SMES as measured by benefit/cost ratios for major categories of applications. As storage capacity increases, cost increases at a rate faster than benefits. As a result, favorable economics are more likely in applications requiring less storage. Transmission system applications requiring dynamic storage appear to have the most attractive economics. Customer service applications may be economic in the near term, but improved ride-through capability of end-use equipment may limit the size of this market over time. Other applications requiring longer storage times appear to be only marginally economic at best. Significant cost reductions (on the order of 50%-75%) or additional benefits must be identified to obtain favorable economics for these applications.

For SMES systems to be commercially successful, they must be both economically attractive in an application and provide performance/cost advantages as compared to competing technologies. The overall assessment of the competitiveness of SMES in electric utility applications is summarized in Exhibit 1-3.

Exhibit 1-2 Range of Potential Benefits versus Total System Cost for Various SMES Sizes

Exhibit 1-3 Summary of SMES Competitiveness in Electric Utility Applications

Application	Typical Size		Primary Competing Technologies	SMES Competitive Position	Annual SMES Market	
	Power (MW)	Storage (MWh)			2000	2030
Generation Peaking	1000	4000	Gas Turbines CAES	Poor	-	-
Generation Stability	400	20	Gas Turbines Batteries	Good	Demo's	1-2/yr
Transmission Stability	500	500 MW-sec	FACTS Batteries	Good	Emerging	5-10/yr
Distributed Storage	5	10	Fuel Cells Batteries	Poor	-	-
Distribution Power Quality	10	20 MW-sec	Batteries Flywheels	Poor	-	-
Customer Service	1	2 MW-sec	Batteries Flywheels	Good/poor ⁽¹⁾	3-10/yr	-

(1) SMES competitive position is strong in the near term and weak in the long term.

SMES appears most promising in transmission stability applications due to its ability to deliver or absorb large amounts of power in a very short period of time, in frequent cycles, without performance degradation. Other technologies can discharge at high power but have to be designed for lesser depth of discharge or be oversized in energy. Estimated market size, assuming successful commercialization is approximately 5 to 10 units per year, of 500 MW/500 MW-sec size.

In the generation stability, transmission stability, and customer service-level power quality applications, SMES may be economically viable, assuming successful commercialization of the technology and allowing for application-specific variation in benefits. Although there will be significant competition in these applications from other technologies, the competitive position of SMES is expected to be good.

In the generation peaking, distributed storage, and distribution-level power quality applications, based on the information currently available, it does not appear that the economic benefits of SMES will exceed its cost in the vast majority of applications and its competitive position relative to competing technologies is poor. Even when multiple benefits are considered, they appear inadequate to make these applications economically viable and as a result, its attractiveness relative to competing technologies is poor.

There is widespread interest within utilities for the development of SMES technology, but there is no general consensus regarding the most attractive size. An underlying attribute which appears to cut across all markets and applications is the ability of SMES to absorb and emit power at a rate faster than any other technology. In order for SMES to obtain a competitive position in any market, future development effort will be required on tools and applications which take maximum advantage of these unique attributes.

1.5.1 Generation Applications

Based on the results of industry interviews, the high priority problems faced by the generation segment of the electric utility industry include (in order of priority):

- Inadequate peak power capacity,
- Need for improved load following,
- Need for better control of bulk power transfers, and
- Economy power for peaking needs.

For *inadequate peak power capacity*, technologies including gas turbines, reciprocating engines, and possibly fuel cells appear to meet the market's needs better than SMES. Given the low capacity factor associated with this application, the emphasis on economics, the low projected cost of natural gas, and the emphasis on low economic and technical risk, it appears that SMES does not have a competitive advantage in this application.

For *load following* and other dynamic generation applications such as providing spinning reserve and reserve margin, batteries and SMES both appear to be potentially competitive. The technical maturity of batteries give them a near term advantage. The potential for SMES to serve other system needs from an installation targeted towards this application may give it additional benefits in some instances.

The ability to *integrate bulk power transfers*, such as from non-utility generators (NUGs) and inter-utility-power transfers appears to favor battery technology over SMES. This application requires technology which can instantaneously pick up or reduce load. More favorable economics and lower risk may favor batteries in this application although the storage capacity required is large for a battery system. Successful SMES development in the 400 MW/100 MWh size range could be competitive in this application given its more favorable charge/discharge characteristics.

For situations where low cost off-peak electricity is available, *economy power for peaking needs* might be attractive. SMES does not appear to have a competitive advantage over conventional alternative storage technologies such as pumped hydro and compressed air energy storage (CAES). SMES appears to be at a relative economic disadvantage versus both pumped hydro and CAES based on current projections of SMES system installed costs. However, CAES has siting constraints and economics which are sensitive to gas costs and pumped hydro has significant siting constraints which limit its use. The features of SMES may make it attractive in situations where neither CAES nor pumped hydro can be used, but it will be limited by its economics relative to generation technologies.

The benefit/cost ratio for generation applications of SMES requiring bulk storage capability, appears to be very low due to the projected high cost of SMES storage. Combined benefits for multiple applications do not appear to influence the benefit/cost ratio significantly. For generation stability applications, the storage requirements are lower and SMES could potentially have a benefit/cost ratio of approximately 1.0, assuming cost and performance goals are successfully achieved.

The system size requirements for the generation stability market would typically be 100-400 MW/10-20 MWh. The benefit/cost ratio of SMES in this application ranges from 0.2 to 2.8 depending upon site specific characteristics and assuming SMES cost/performance goals are met. By the year 2000, there could be a need for demonstration projects to provide operational experience and substantiate projected benefits. Successful development of this size of SMES and substantiation of the benefits of SMES in these applications could lead to a potential market of 1-2 units per year of 100-400 MW/10-20 MWh systems by the year 2030. Battery energy storage systems will most likely be the primary competitor in this market.

- The competitiveness of SMES in generation applications is discussed in more detail in Section 5.

1.5.2 Transmission Applications

Based on the results of industry interviews, the high priority problems faced by utilities in the transmission area of the electric utility industry include (in order of priority):

- Insufficient transfer capacity,
- Voltage regulation/stability/quality,
- Flow control/loop flows/bottlenecks, and
- Stability (transient/dynamic).

For situations where *insufficient transfer capacity* of the transmission system is a problem, the traditional approach of *expanding/upgrading* lines appears to be the most competitive option, having more attractive economics than SMES in most applications. However, siting of new transmission lines will be increasingly difficult in the future.

For *voltage regulation/stability/quality* applications requiring the deliver/absorption of real power, SMES may be very competitive. This application of high power capacity/short duration energy storage matches SMES characteristics well. A major competing technology for this application is battery storage. The advantages of SMES over batteries includes very high energy charge/discharge, low maintenance, long life, and low environmental impact.

For *flow control/loopflow/bottleneck* applications, Flexible AC Transmission Systems (FACTS) compensation/regulation or upgraded transmission lines appear to be more attractive than SMES. Upgrading transmission lines is the most reliable near-term method of increasing transfer capacity and will continue to be preferred. FACTS technology specifically targets problems such as these and is likely to be favored in the future.

SMES may be very competitive in *transmission stability* applications requiring high power capacity/short duration energy storage. Stability of transmission systems will become more important in the future as greater demands are placed on systems. The major competing technology in this application will be battery systems. The competitive advantage of SMES is similar to that in voltage regulation/stability/quality applications.

The device size for transmission stability control will typically be 400-600 MW/400-600 MW-sec. The benefit/cost ratio for SMES in this application is approximately .3 to 2.2, depending upon site specific characteristics and assuming SMES cost/performance goals are achieved. The year 2000 market is expected to be negligible. In the year 2030 market, SMES and battery energy storage systems will compete for market share with FACTS and conventional technologies; we estimate the SMES market size to be 5 to 10 units per year at a system size of 500 MW/500 MW-sec.

The competitiveness of SMES in transmission applications is discussed in more detail in Section 6.

1.5.3 Distribution Applications

Based on the results of industry interviews, the high priority problems faced by utilities in the distribution area of the electric utility industry are (in order of priority):

- Problems related to generation additions at the distribution and end-use levels,
- Power quality and reliability problems, and
- To a lesser extent, capacity limitation problems (both equipment overloads and excessive fault levels).

The problems created by *generation additions* at the distribution and end-use levels are best solved by protection system and distribution upgrades. In general, energy storage technology is not applicable to addressing this type of distribution problem.

The *power quality and reliability* problems associated with long duration variations and interruptions are also best solved by protection system and distribution upgrades. For selected commercial and industrial applications, storage device solutions may have merit when applied to power quality problems associated with short duration variations and interruptions. For the majority of distribution feeders, however, there is too wide a range of customer types and needs to merit such application for power quality purposes. In general, the high energy storage and operating costs of SMES technology relative to batteries and flywheels will create a poor competitive position for SMES in voltage sag applications at the distribution level.

The problems of *distribution-level capacity limitations* are typically solved by a combination of solutions such as distribution equipment upgrades, demand-side load management, distribution automation, and protection system upgrades. In general, storage solutions are more costly compared with these conventional solutions, although storage may become more feasible when the benefits are simultaneously realized at the transmission and generation level. The high energy storage and operating costs of SMES technology relative to batteries and flywheels will severely limit the market opportunity for SMES in distribution load-leveling applications.

The competitiveness of SMES in distribution application is discussed in more detail in Section 7.

1.5.4 Customer Service Applications

The high priority problems faced by the customer service segment of the electric utility industry include:

- power quality, and
- improved energy utilization.

Power quality applications utilize SMES units in limited commercial production at the present time, with no direct competition. These SMES units appear to be exploiting a niche opportunity. The portable nature of the system offers flexibility in being able to support an immediate customer need for power quality improvement. However, as the market needs develop, battery systems, flywheel, or electro-chemical capacitor technology are likely to be developed and all are likely to have a cost advantage relative to SMES. Due to the importance of low initial capital cost for customer acceptance, systems incorporating high-volume automotive battery technology would likely dominate the market by the year 2000 (assuming a significant market develops). The major disadvantages of SMES systems in this application (e.g., 2 MW/2 MW-sec) are high capital and operating costs.

In the long term, the *end-use load-leveling/power quality* market will be primarily driven by cost. In this time frame, it is unlikely that SMES will be cost competitive against competing technologies being manufactured in high volumes (e.g., improved batteries, flywheels, electro-chemical capacitors). The use of batteries or flywheels in electric vehicles, for example, would give these storage technologies a high volume manufacturing cost advantage which would carry over into customer service applications. It is unlikely that the market for smaller SMES systems, even allowing for economies of scale in superconductor manufacture, would be large enough to provide competitive costs from manufacturing economies of scale. Low manufacturing costs resulting from high volume manufacturing to supply other larger markets will most likely determine which technologies dominate the customer service market.

The competitiveness of SMES in customer service applications is discussed in more detail in Section 8.

1.6 Recommendations

Based on our review of the needs in the marketplace, the capabilities of SMES, and the characteristics of the competing technologies, SMES technology commercialization would be facilitated if the following "non-hardware" needs were addressed:

- Engineering modeling tools which accurately reflect the performance characteristics of SMES need to be developed to assist utility system planners and others to better understand the benefits of SMES and its' interaction with the utility system.

- Conceptual designs should be developed for SMES systems targeted to the high priority utility needs where SMES has a potential competitive advantage. Design optimization will help to more accurately determine where SMES has significant competitive advantage and will provide improved capital and operating cost projections.
- The impact of public concerns regarding static (DC) electro-magnetic fields must be more fully explored in order to fully understand the potential public opposition which may develop for large-scale deployment of SMES.
- More detailed specifications regarding acceptable EMF levels in the various potential market applications should be developed and compared against likely SMES designs. The relative cost effectiveness of toroidal designs need to be more fully explored with respect to potential benefits in terms of very low EMF.
- The distribution of benefits within the various utility market segments needs to be more fully explored. Additional site specific studies to quantify benefits, coupled with improved cost estimates, will provide a better understanding of the attractiveness of SMES. Specific efforts aimed at understanding the interaction of benefits across market segments for high priority applications (SMES devices smaller than ETM size) will expand this knowledge.
- There is an apparent need to assess the costs and benefits of micro-SMES and competing technologies such as SLI batteries and flywheels in specific customer service demonstrations. Comparative demonstrations of micro-storage technologies focused on power quality improvement would help to substantiate differences.
- A more thorough characterization of the voltage sag problem and the cost to specific industries should be determined. For specific high value added industries there is a need to characterize scrap losses, time required to restart the process, the sensitive equipment used, etc... A more accurate assessment of the value and market size of customer service applications could then be determined.

1.7 Limitations of Analysis

Any assessment of potential new market opportunities is subject to limitations imposed by available data, methodological imperfections and available resources. These limitations introduce uncertainty into the final assessment in a number of different ways. This assessment of potential electric utility applications for SMES is subject to uncertainty due to the following factors.

- Because SMES is still an emerging technology, the available cost estimates for systems are based on work and designs which are subject to substantial revisions as the technology develops. Every attempt has been made to use the best cost data currently available, to allow for cost reductions as the technology matures, and to utilize a range of cost estimates which bracket the likely costs of the

technology. Although it is considered unlikely, if system costs can be substantially reduced (e.g. by 50%-75%) below those used here, potential market size estimates developed in this assessment would be impacted (increased).

- The valuation of the benefits of SMES in electric utility applications are subject to uncertainty similar to that associated with costs. Uncertainty exists over the full extent of benefits which may be captured by SMES. Also, the type and magnitude of benefits varies from site to site and relatively few specific site studies have been performed. The methodology used in this study extracted specific benefit trends from the available data and extrapolated these trends to the types and magnitude of benefits available in generic applications. New types of benefits not currently envisioned for SMES or benefit magnitudes substantially larger than expected would impact (increase) the market potential estimates developed in this analysis.
- The size of the applications examined for SMES technology cover 7 orders-of-magnitude in storage capacity and 4 orders-of-magnitude in power output. This tremendous variation in size poses limitations on any analysis methodology. Because of site specific variations in cost and benefits, the actual attractiveness of SMES at any given site may differ from the results for typical sites presented in this analysis. However, the conclusions presented in this analysis regarding the prioritization of potential applications and the identification of the most attractive opportunities will be relatively insensitive to these variations.
- The economic analysis of potential SMES applications has been performed using baseline forecasts for fuel and electricity prices. The typical variations found in fuel price scenarios between various sources (e.g. as published by EIA and others) do not substantially impact the results of this analysis. A scenario in which off peak electricity costs decrease over time (e.g. due to renewed focus on nuclear power) and natural gas prices increase substantially (e.g. due to deliverability or supply constraints) would enhance the value of energy storage technologies for supplying peak and intermediate power needs. However, this type of scenario is considered to be relatively unlikely over the time horizon of this study.
- Changes are occurring in the dynamics of the electric utility marketplace due to the National Energy Policy Act of 1992, the move to competitive bidding and Integrated Resource Planning, and other forces in the marketplace. These changes could result in an increased focus on wheeling, transmission and distribution services on the part of electric utilities. If, as a result, utilities emphasize power delivery more than generation in the future, the value of the benefits of SMES technology (especially in T&D applications) could change. Due to the significant uncertainties associated with these forces, we have not attempted to account for their potential effects in this analysis.

2.0 Introduction

2.1 SMES Technology

Superconducting magnetic energy storage (SMES) is an emerging technology with several features that are attractive for electric power applications. SMES is unique in its potential to perform a diverse range of functions, from bulk storage of electricity to transmission line stabilization and customer power quality enhancements. SMES technology has the potential to provide high value to utilities by serving several functions from a single installation. It has siting flexibility and can be located centrally, similar to central station power plants, or applied in multiple smaller installations at the distribution or customer level.

SMES systems have been studied extensively since the 1960s as a means of storing electricity in the magnetic field produced by current flowing in a coil or inductor. Current SMES designs are based on storing energy in the magnetic field produced by DC current flowing in a superconducting coil. Energy is transferred into and out of the coil through solid state power conversion equipment. Two basic configurations have been studied for commercial application, one based on solenoid coils, the other on toroidal coils. The most common designs being pursued in the U.S. are based on a solenoid coil. The large forces associated with the magnetic fields produced by SMES units require significant support structures. SMES systems with energy storage capacity greater than about 20-50 MWh typically integrate the support structure into the ground to most effectively manage the large forces. The systems utilize struts or straps which contact the "warm" earth near the cryostat and are typically referred to as "warm supported." SMES systems with storage capacity of less than about 20 MWh can utilize free-standing structural steel supports because of smaller forces. These structures typically utilize hoops which direct contact with the cold cryostat and are referred to as "cold supported."

Small 1 MW/1 MW-sec SMES devices are currently in limited commercial production. Trial installations have been made for power quality enhancement at commercial customer manufacturing facilities. Superconductivity, Inc. (SI) of Middleton, Wisconsin, offers units with storage capacities of several hundred watt-hours and power conditioning systems (PCS) in the range of 0.5 MW to 2.5 MW. The largest SMES unit built in the U.S. to date is the "Tacoma SMES" constructed by DOE and Los Alamos National Laboratory for Bonneville Power Administration (BPA) at its Tacoma Substation in 1983. This 10 MW/30 MW-sec cold-supported device successfully eliminated a 0.35 Hz subsynchronous oscillation on the BPA system and completed a million on-line charge/discharge cycles with no degradation of the superconductive coil structure. No earth-supported SMES systems, needed for larger storage capacity applications, have been built to date.

A program was initiated in 1987 to develop an Engineering Test Model (ETM) of an earth-supported SMES. Sponsored by the Strategic Defense Initiative Organization (SDIO) of the U.S. Department of Defense, the purpose of the ETM was to demonstrate the potential of SMES through the fabrication, operation, and performance of a 400 MW/20 MWh earth-supported SMES unit. Scale-up to large earth-supported SMES systems such as those proposed for large utility applications

entails substantial effort, investment, and risk. Successful demonstration of the ETM would facilitate scale-up to larger earth-supported commercial SMES units (e.g., 1000 MW/10,000 MWh for utility storage applications).

The Defense Nuclear Agency (DNA) managed the SMES program for the Strategic Defense Initiative Organization (SDIO) from 1987 to 1990. In 1990, Congress transferred the SMES program to DNA. DNA is currently evaluating, in coordination with the U.S. Department of Energy (DOE), potential opportunities for SMES in civilian applications. The potential technological competitiveness of SMES in various potential markets (vis-a-vis both existing and likely emerging competing technologies) is being evaluated. This data will be used along with other information as input to the DNA/DOE decision on the nature, role, and extent of commercialization support for SMES.

2.2 SMES Costs and Benefits

Initially viewed primarily as a technology for bulk energy storage, SMES systems are currently seen as an option for transmission system, distribution system, and customer service applications as well (see Exhibit 2-1). The capital cost of SMES technology varies greatly across this range of potential applications. For bulk power storage applications, specifications call for large amounts of energy (>1000 MWh) to be stored and discharged relatively slowly (hours). This requires large superconducting coils, and therefore large amounts of magnetic storage material which dominate the capital costs. In smaller power quality or customer service applications, the needs are for small amounts of energy storage, but with rapid charge and discharge characteristics (milliseconds). In these applications, the power conditioning and control electronics dominate the capital costs.

SMES technology is unique in its potential to be tailored to the specific needs of power systems by offering high efficiency in large size applications, high charge and discharge rates, and/or diurnal storage capability. Benefits from the variety of applications which have been suggested for SMES include improving voltage stability, voltage regulation, transmission line deferral, improved system reliability, loss reduction, and reducing the need for reactive power regulating facility requirements. SMES systems also have benefits for distribution system applications, such as improving power supply reliability (shortening blackout time), deferral of substation facility upgrades by load leveling, and reducing reactive power regulating facility requirements. Combinations of these benefits from a single installation are hoped to make SMES technology more economically attractive than competing technologies.

Environmental benefits for applications of SMES lie in reduced emissions from fossil power generating sources. However, concerns have been raised about the degree to which electro-magnetic fields (EMF) produced by SMES may inhibit its application. The degree to which site constraints will exist for SMES systems due to EMF concerns will need to be carefully addressed to understand the technology's potential.

Exhibit 2-1 Typical Proposed Electric Utility SMES Applications

2.3 Report Organization

This report is organized into 12 sections.

Section 1	Summarizes the overall results and conclusions of this study.
Section 2	Provides a brief introduction to SMES technology development and this project.
Section 3	Provides an overview of the methodology employed to conduct this analysis.
Section 4	Reviews the development of the cost data used in this analysis for SMES and the competing technologies.
Sections 5,6,7,8	Analyze potential applications and the technological competitiveness of SMES in the electric utility generation, transmission, distribution, and end-use market segments.
Section 9	Presents a summary of the likely benefits of SMES technology and the expected benefit-to-cost ratios.
Section 10	Presents the likely market penetration of SMES technology in the four electric utility market segments.

Section 11 Reviews several specific technological aspects of SMES technology relevant to it's commercial acceptance—EMF concerns, refrigeration loads, and losses.

A detailed listing of references used in this study along with additional sources of information is included in the bibliography.

3.0 Methodology

3.1 Overview

Evaluating the potential of a developing technology such as SMES poses an interesting methodological challenge. On the one hand, many of the characteristics of SMES are still uncertain in terms of both the likely cost and the likely performance of the fully commercialized technology. The type, cost, and performance of competing technologies also has uncertainty associated with it. At the same time, the utility problems SMES is targeted for have a large range in the value (benefit) of resolving the problem. The mix of problems also varies significantly from one utility to another. Even within a single utility the mix of problems and the range of benefit values is likely to change with time, as the power system develops. The methodology chosen must be consistent with this significant uncertainty in costs and wide variability in benefits.

A product development approach was chosen to assess the potential applications for SMES for this study. A product development approach focuses on the needs of the marketplace, the capabilities of SMES, and the characteristics of the competing technologies. The approach establishes the nature and *relative* importance of key buying factors in each of the potential applications of interest. The *relative* performance of SMES and various competing technologies is then assessed against the key buying factors which have been identified. This information is used to identify those application areas where SMES might have a potential competitive advantage to fill the needs of the market better than other technologies. The approach starts from a broad view of the market and its needs and then focuses in to put the key technological competitiveness issues into perspective. The approach is systematic and produces reproducible results which can be built on in subsequent work as key issues are defined for further investigation. The results are relatively less sensitive to variability in assumptions (e.g., costs, benefits) than other approaches.

Our overall approach encompasses five basic steps as outlined in Exhibit 3-1:

- **Step 1** Assess high priority utility problems;
- **Step 2** Determine criteria with which utilities evaluate problem solutions,
- **Step 3** Identify and characterize potential technological solutions,
- **Step 4** Evaluate potential technological solutions for priority problems using defined criteria to assess SMES competitiveness, and
- **Step 5** Assess SMES markets.

These steps were supported via a number of methodological development and data gathering activities. Each of these steps is discussed in more detail below.

Exhibit 3-1 General Methodology for Assessing SMES

3.1.1 Market Segmentation

For purposes of assessing the needs of the electric utility marketplace, we have segmented the market into four segments:

- **generation:** that part of the utility industry involved in generating electricity from primary fuels (e.g., gas, coal, hydro, solar) and providing bulk power to the transmission system;
- **transmission:** that part of the utility industry involved in transferring bulk power at high voltages (>34 kV¹) from generators to the local distribution grids;
- **distribution:** that part of the utility industry involved in receiving bulk power from the transmission system and distributing it (at voltages <34 kV) to the ultimate end-use customers; and
- **customer service:** the eventual end-use customers for electricity, including residential, commercial, industrial, institutional, and agricultural users.

¹ although in some utilities, even 34kV is considered a transmission voltage

Within each segment the same overall approach has been used, as discussed below.

3.2 Step 1—Assess Utility Problems

3.2.1 Relative Importance of Problems

The first step involved determining which of the utility problems potentially solvable with SMES technology were of greatest importance (and hence value) to the utilities. For each segment, a prioritized list of the major problems being faced by that segment of the utility industry was first developed. Based on previous work, especially the DOE SMES Workshop results,^[2, 3, 12] a list of possible problems for which SMES is a potential solution was developed. This list was then used in a series of interviews with U.S. utilities to:

- carefully define each problem,
- determine the relative importance of the problems (high/medium/low) to each utility,
- determine which problems were not relevant, and
- identify any other critical problems each utility was faced with.

The ranking of problems provided by each utility was weighted by their respective generation capacity to produce results representative of the market segment.

As part of the interview process, significant effort was spent to accurately define the nature of the specific problems in each market segment. Based on the interviews, additional analysis, and in some cases additional interviews, root cause(s) of the major problems were categorized. Based on the root cause analysis, problems were aggregated into families of related problems and/or those requiring similar solutions.

Although the nature of the interview questions and the number of utilities interviewed did not allow a statistically-based sampling approach to be used, a broad range of utility sizes and geographic locations were used. A total of 17 utilities were interviewed in the generation segment, 12 in the transmission segment, 8 in distribution, and 2 in customer service. Twelve additional interviews were conducted with end users and others in the customer service segment. Several other utilities were contacted during the course of the study, however, detailed interviews were not conducted.

Results of the Step 1 analysis are shown in a "Problems Matrix" for each of the four market segments. The Problems Matrix summarizes the interview results and the overall relative priority of each problem. A sample Problems Matrix is shown in Exhibit 3-2. From the ranking of problems in the Problems Matrix, a relative weighting was developed for each problem which is used later in the technology comparison.

The results of the analysis for each market segment, are discussed in the respective market segment section (Sections 5, 6, 7, 8).

Exhibit 3-2 Sample Problems Matrix

SAMPLE PROBLEMS MATRIX

WHATs vs. HOWs	
Serious Problem/Need	●
Average Problem/Need	○
Minor Problem/Need	○

	WEIGHT	Inadequate Peak Power Supply	Reduce Peak Cost	Need for Improved Load-Follow	Integrate Bulk Transfers	Inadequate Spinning Reserve	Automatic Generation Control
Utility #1	2	○	○	○	○	○	○
Utility #2	1	○	○	○	○	○	○
Utility #3	3	●	○	○	○	○	○
Utility #4	2	○	○	○	○	○	○
Utility #5	1	○	○	○	○	○	○
Weighted Total		53	41	57	33	33	21
Rank		2	3	1	4	4	6

3.2.2 Value/Benefit of Solving Problems

As part of the problem assessment, it was also necessary to collect information on the relative magnitude of the benefit of correcting (or partially correcting) the problem. It is very difficult to accurately assess the benefit of solving many of the utility problems SMES is targeted towards, especially the dynamic transmission and distribution problems. Several reasons contribute to this difficulty:

- The value of benefits is very site specific. Even within a single utility, the value of solving a problem can vary from load center to load center.
- There is a limited amount of good benefits data from previous work which is publicly available (fewer than 10 good case studies), especially for transmission, distribution, and end-use problems. In part, this is because of the site specific nature of the benefits. The complexity of some of the problems involved also makes benefits assessment difficult.
- The methodology for accounting for benefits, how they add across market segments and how costs should be accounted for varies widely and results are often not comparable. The additive nature of benefits varies significantly from site to site, dependent on local needs. This can contribute to variations in benefit values.

Because inadequate primary data was available for statistically valid comparisons, this effort focused on getting acceptable data and using the data to assess the relevant ranges of benefits.

The main sources of benefits data were primary sources e.g. utility interviews,^[170,171,172,173] the BPA Tacoma project (a SMES test program),^[16] a series of benefits evaluations done for BPA,^[75,133] the Chino battery test program,^[84] selected EPRI studies (especially in distributed generation),^[94,95,92] SMES-ETM related studies and analysis,^[15] and selected utility studies (e.g., for distributed PV systems^[157]).

All of the problems examined show wide variability in the value of the benefits from site-to-site, even when normalized to a \$/kW or \$/kWh basis. The longer term storage benefits (e.g., in generation) have somewhat less variability from utility to utility (e.g., $\pm 50\%$ - $\pm 100\%$), while the short term control and protection benefits (e.g., in transmission stability control) can vary by a factor of 10 from site to site. In all cases, the benefits estimates in this analysis should be taken as likely ranges for typical applications.

The causes of this variation as well as the results of the benefits analysis are discussed in more detail in Section 9.

3.3 Step 2—Determine Evaluation Criteria

The second step involved developing a list of the criteria used by utilities to evaluate potential solutions to their priority problems identified in Step 1. The criteria and the weighting which utilities apply to them are assessed consistently across problems in any one of the four segments. These weightings are an assessment of the relative importance that a given utility places on these criteria when making an investment decision. The definition of the evaluation criteria and the relative importance of the criteria varies between the market segments. Based on the difference in relative importance, different weights were assigned to the criteria in each market segment. For each segment, a preliminary list of potential evaluation criteria was developed and reviewed as part of the utility interviews.^[170, 171, 172, 173] The utility interviews were used to

- validate the criteria,
- add/delete criteria, and
- determine the relative importance (high/medium/low) to the utilities of different criteria.

Utility responses were weighted by generation capacity and an overall criteria weight representative of the segment was developed. As noted above, overall criteria weights varied between each segment. Individual criteria were grouped into five major categories: technical, economic, environmental, risk, and other. In addition to the weights assigned to individual criteria, the total weights assigned to each category were cross-checked to ensure that relative category weights were reasonable. For example, in the generation segment, the category weights are: technical—35%, economic—30%, environmental—20%, risk—11%, other—4%. In the transmission segment technical criteria received 50% weight, while economic criteria received 20% weighing.

Results of this analysis are summarized in a "Criteria Matrix" for each of the four market segments which summarizes the utility interview results and the overall relative priority of each criteria. A sample Criteria Matrix is shown in Exhibit 3-3.

The results of the analysis for each market segment, are discussed in the respective market segment section of the report (Sections 5, 6, 7, 8).

3.4 Step 3—Characterize Potential Solutions

The third step involved identifying potential solutions to the electric utility priority problems from Step 1 and characterizing each potential solution vis-a-vis the evaluation criteria defined in Step 2.

For each problem area, a working list of potential solutions was identified. These included current technologies, likely emerging technologies, and SMES technology. For each technology, the relative performance vis-a-vis relevant criteria (defined in Step 2) was assessed by an appropriate technical specialist. As part of this review,

Exhibit 3-3 Sample Criteria Matrix

SAMPLE CRITERIA MATRIX

WHATs vs. HOWs

Very Important	●●●
Important	●●○
Not Important	○●○

	WEIGHT	TECHNICAL PERFORMANCE	ECONOMIC	Revenue Requirements	Capital Costs	ENVIRONMENTAL ISSUES	EMF	Air Quality	RISK	Technical Maturity/Support	OTHER	Construction lead time
Utility #1	2	●	●	●	●	●	●	●	●	●	●	●
Utility #2	1	●	●	●	●	●	●	●	●	●	●	●
Utility #3	3	●	●	●	●	●	●	●	●	●	●	●
Utility #4	2	●	●	●	●	●	●	●	●	●	●	●
Utility #5	1	●	●	●	●	●	●	●	●	●	●	●
Weighted Total		81	81	81	81	81	81	81	77	77	49	49
Rank		1	1	1	1	1	1	1	6	6	7	7

careful attention was paid to technical characteristics of SMES and competing technologies which were potential sources of competitive advantage. Current performance characteristics were based on a variety of interviews and primary data (detailed in each of the segment discussions - Sections 5,6,7,8). Long-term performance characteristics were based on available published information and professional judgement.

In identifying possible solutions to priority problems, the focus was on the solution typically applied to the root-cause problem. Because of the inter-related nature of electric power systems, problems can often be addressed in several different ways if a primary solution is not feasible. For example, a transmission capacity problem might be addressed by Flexible AC Transmission System (FACTS) technology, transmission system capacity increase, or diurnal storage. To keep the number of solutions analyzed within reasonable limits, the focus was on the typical solution to the root cause problem, assuming no unusual constraints.

The results of the technology characterization for each market segment are discussed in the respective market segment section of the report (Sections 5, 6, 7, 8).

For each technology, estimates were also developed for relevant economic parameters, including capital cost, operating costs, maintenance costs, fuel efficiency, etc. For non-SMES technologies, these costs were based on data in the ADL Advanced Power Generation Database and/or generally accepted reference data (e.g., EPRI TAG.^[144] For the costs of emerging technologies, available literature and interview information were used along with professional judgement. Long-term economic characteristics were judgmentally developed assuming constant real costs for basic technologies, adjusted for technology improvements and any applicable learning curve effects.

For SMES, cost estimates were developed based on the limited primary data available and relevant literature.

The cost estimates and economic parameters are discussed in detail in Section 4.

3.5 Step 4—Evaluate SMES Competitiveness

3.5.1 Economic Analysis

The economic analysis performed varied from segment to segment, depending upon the relevant economic criteria defined during the utility interviews for that segment. In the generation segment, revenue requirements were identified as the most important economic parameter. In the transmission, distribution, and end-use segments, where the benefits were dynamic event-oriented in nature, capital cost and O&M costs were identified by utilities as the most important criteria.

Revenue requirements were calculated for each technology based on its life-cycle costs, including capital costs, interest during construction, allowable return on equity,

taxes and insurance, income taxes, O&M costs, and fuel charges (where appropriate). Capital charges were based on a typical utility capital structure and typical cost of capital and debt. Life-cycle costs were levelized and expressed on an appropriate basis (\$/kWh, \$/MW/year). For generation economics, results have been displayed as a function of load factor to illustrate the influence of this key variable.

The results of the economic analysis for each market segment are discussed in the respective market segment section of the report (Sections 5, 6, 7, 8).

3.5.2 Technology Competitiveness

In Step 4, the technology alternatives identified in Step 3 were evaluated using the criteria developed in Step 2, as to their effectiveness in addressing the priority problems defined in Step 1.

The technical criteria were first used to evaluate the effectiveness of each technology in solving the individual problem areas. These overall technical rankings were used with the problem weights and the weighted non-technical criteria (economic, environmental, risk, other) to evaluate the overall technological competitiveness of the competing technologies in the individual market segments. Results are summarized in a "Technology Competitiveness Matrix" for each of the four market segments. A sample Technology Competitiveness Matrix is shown in Exhibit 3-4.

The results of the analysis for each market segment are discussed in the respective market segment section of the report (Sections 5, 6, 7, 8).

3.6 Step 5—Assess SMES Markets

3.6.1 Benefit/Cost Ratios

The benefit estimates developed in Step 1 for each problem were used with the annualized values of SMES costs developed in Step 3 to produce benefit/cost ratios. The mid-point values of the cost range and the benefit range were used to calculate benefit/cost ratios. Given the wide variability associated with SMES costs, the ratios have a significant degree of uncertainty. However, they are indicative of the values likely for typical SMES applications and support the general SMES market conclusions drawn in this report.

The results of the benefit/cost analysis are presented in Section 9.

Exhibit 3-4 Sample Technology Competitiveness Matrix

SAMPLE TECHNOLOGY COMPETITIVENESS MATRIX

WHATs vs. HOWs					
Strong Characteristic		●	5		
Average Characteristic		○	3		
Weak Characteristic		○	1		
	WEIGHT	Pumped Hydro	CAES	Gas Turbines	Small SMES (100MW/20MWh)
ECONOMIC					
Revenue Requirements	9	○	●	●	○
Capital Costs	8	○	●	●	○
GENERATION SYSTEM NEEDS					
Peak Power Supply	12	○	○	●	○
Reduce Peak Cost	7	●	●	○	○
ENVIRONMENTAL ISSUES					
EMF	6	○	○	○	○
Air Quality	6	●	○	○	●
RISK					
Technical Maturity/Support	6	●	○	●	○
OTHER					
Construction lead time	4	○	○	●	○
Weighted Total		3 350	2 370	1 411	4 150
Rank		3	2	1	4

3.6.2 Market Potential

The market size for technologies in all four market segments is related to the demand growth for electricity. Electricity demand forecasts generated by the North American Electric Reliability Council (NERC), DOE and others^[142,158] were used as a basis to understand the market potential. In each market segment the underlying trends were identified in order to identify future departures from historical patterns:

- In generation, the projection of the need for peaking and storage capacity was developed from a combination of historical patterns, published forecasts and utility interviews.^[171]
- In transmission and distributions the problems identified in the Problem Matrices were considered in light of the system needs and driving forces to develop a projection of the magnitude of the market for solving those problems.
- For the customer service market, UPS market data^[146] and industry estimates regarding the need for power quality solutions were used to estimate the market potential.

The benefit/cost ratios were combined with the results of the Technology Competitiveness Matrices and the assessment of total market size to determine the likely market penetration for SMES in each potential application. In order for SMES to achieve market penetration in a given segment or application, a potential benefit/cost ratio of one (1.0) or more and costs competitive with other potential technologies and solutions were required. Applications with benefit/cost ratios much less than one (1.0) are unlikely to obtain substantial market share. Given the basic uncertainty in costs, uncertainty in performance of emerging technologies and the large variability in benefit values, more elaborate market analysis was deemed to be of limited value at this time. The basic results presented are relatively insensitive to small variations in cost.

3.7 Limitations of Analysis

Any assessment of potential new market opportunities is subject to limitations imposed by available data, methodological imperfections and available resources. These limitations introduce uncertainty into the final assessment in a number of different ways. This assessment of potential electric utility applications for SMES is subject to uncertainty due to the following factors.

- Because SMES is still an emerging technology, the available cost estimates for systems are based on work and designs which are subject to substantial revisions as the technology develops. Every attempt has been made to use the best cost data currently available, to allow for cost reductions as the technology matures, and to utilize a range of cost estimates which bracket the likely costs of the technology. Although it is considered unlikely, if system costs can be

substantially reduced (e.g. by 50%-75%) below those used here, potential market size estimates developed in this assessment would be impacted (increased).

- The valuation of the benefits of SMES in electric utility applications are subject to uncertainty similar to that associated with costs. Uncertainty exists over the full extent of benefits which may be captured by SMES. Also, the type and magnitude of benefits varies from site to site and relatively few specific site studies have been performed. The methodology used in this study extracted specific benefit trends from the available data and extrapolated these trends to the types and magnitude of benefits available in generic applications. New types of benefits not currently envisioned for SMES or benefit magnitudes substantially larger than expected would impact (increase) the market potential estimates developed in this analysis.
- The size of the applications examined for SMES technology cover 7 orders-of-magnitude in storage capacity and 4 orders-of-magnitude in power output. This tremendous variation in size poses limitations on any analysis methodology. Because of site specific variations in cost and benefits, the actual attractiveness of SMES at any given site may differ from the results for typical sites presented in this analysis. However, the conclusions presented in this analysis regarding the prioritization of potential applications and the identification of the most attractive opportunities will be relatively insensitive to these variations.
- The economic analysis of potential SMES applications has been performed using baseline forecasts for fuel and electricity prices. The typical variations found in fuel price scenarios between various sources (e.g. as published by EIA and others) do not substantially impact the results of this analysis. A scenario in which off peak electricity costs decrease over time (e.g. due to renewed focus on nuclear power) and natural gas prices increase substantially (e.g. due to deliverability or supply constraints) would enhance the value of energy storage technologies for supplying peak and intermediate power needs. However, this type of scenario is considered to be relatively unlikely over the time horizon of this study.
- Changes are occurring in the dynamics of the electric utility marketplace due to the National Energy Policy Act of 1992, the move to competitive bidding and Integrated Resource Planning, and other forces in the marketplace. These changes could result in an increased focus on wheeling, transmission and distribution services on the part of electric utilities. If, as a result, utilities emphasize power delivery more than generation in the future, the value of the benefits of SMES technology (especially in T&D applications) could change. Due to the significant uncertainties associated with these forces, we have not attempted to account for their potential effects in this analysis.

4.0 Cost of SMES and Competing Technologies

4.1 Background

4.1.1 Components of Capital Cost for All Technologies

To ensure comparable development of total capital cost for all technologies, the components of cost have been individually estimated and then aggregated. The components used are shown in Exhibit 4-1.

Exhibit 4-1 Components of Total Capital Cost

Total Plant Investment	
Base cost	_____
Direct construction cost	_____
Indirect construction cost	_____
Contingencies	_____
Interest during construction	_____
Start-up cost	_____
Working capital	_____
Land acquisition	_____

Direct construction costs include field labor, materials and supplies, and factory equipment; indirect construction costs include indirect field labor, tools and facilities, and field engineering and design. Costs that are expected but not known in detail and costs that cover the uncertainty of the cost estimate itself are included in the contingency component.

Sources of information for costs for SMES and competing technologies are discussed in more detail below.

4.1.2 Components of Capital Cost for SMES

The costs of a SMES system can be separated into two main components: coil and refrigeration system cost, and the power conditioning system (PCS) cost. The coil/refrigeration system cost is related to the energy storage capacity of the system and whether the coil is cold-supported or earth-supported; it is almost independent of the power capacity of the system. The PCS cost is mostly dependent on the power capacity of the system and is nearly independent of the energy storage capacity. The power conditioning related costs are expressed in dollars per kilowatt of power capacity (\$/kW) while the energy storage related costs are shown in dollars per kilowatt-hour of storage capacity (\$/kWh).

The SMES cost estimating structure is illustrated in Exhibit 4-2. From the SMES cost breakdown and the contribution of the energy storage capacity and the power capacity on the total capital cost, it is expected that for SMES systems with lower energy storage capacity the total cost will be dominated by the PCS cost while the cost of SMES systems with larger energy storage will be dominated by the

coil/refrigeration system cost. The pie charts of Exhibit 4-3 illustrate the variation in capital cost structure for different size SMES units.

Exhibit 4-2 SMES Capital Cost Estimating Structure

Cost estimates for the commercially available 1 MW/1 MW-sec cold-supported SMES units^[8,75,82,91] were used with predictions of how costs would decrease as these units become more fully commercialized to estimate the costs of cold-supported SMES systems in this size range.

Little good primary data is available on the estimated capital costs for earth-supported SMES devices. Detailed cost estimates are being prepared by both contractors on the earth-supported SMES Engineering Test Model (SMES-ETM) program^[89,90]. Preliminary versions of this information have been released for use in the workshops^[2,3,11] and this study. These SMES cost data were compared with other available literature data^[e.g., 8,13,75,82] available at this time. However, none of this secondary data is supported by the detailed cost analysis associated with the SMES-ETM estimates. Data was adjusted to reflect commercialization of the technology and to account for cost reductions due to learning curve effects and technology refinements.

The cost estimates for earth-supported SMES units have considerable uncertainty associated with them because the SMES-ETM design is still undergoing major changes, the cost estimates are sensitive to the system design and SMES costs for

Exhibit 4-3 Capital Cost Breakdown for Selected SMES Systems (Year 2000, \$ 1992)

SMES-ETM and larger units are "site" sensitive due to the extensive site construction work required. Nevertheless, the SMES-ETM estimates are the best data available for earth-supported SMES units in the 400 MW/20 MWh size range.

There is little good data available for earth-supported SMES systems larger in size than the SMES-ETM. As part of the SMES-ETM program, cost estimating models are being developed to project the likely costs of SMES units in the 1000 MW/1000 MWh size range; the uncertainty in the cost estimates from these models is greater than that associated with the SMES-ETM, because the conceptual design for the large scale SMES has not been done. The trends being developed in these models for capital cost versus size were used to project likely costs for SMES systems in the 1000 MW/1000 MWh size range.

Coil/Refrigeration System Costs. The coil/refrigeration system is composed of the superconducting magnetic coil and associated support structure, and the refrigeration system required to cool the coil to superconducting temperature (2-4K).

The refrigeration system capital cost is about 1 to 2% compared to the coil cost for units with energy storage capacity over 1 MWh. There is the potential to reduce the refrigeration equipment cost component with the usage of high-temperature superconductors (HTS) with operating temperatures of the superconducting coil of

about 77K. HTS coils might also be desirable, for example, to reduce refrigeration operating costs. The only disadvantage is that by using HTS the coil cost might be increased by a factor of two to four^[39]. This is ultimately dependent on the current carrying capability and wire cost of HTS which is highly uncertain. Given the small contribution of the refrigeration system to total capital cost, any modest reduction in refrigeration system cost would have a negligible effect on total capital cost.

The cost of the superconducting coil is dominated by material costs. These costs include the superconductor cost and the structural support cost. For SMES units with energy storage capacity less than 50 MWh, the superconductor cost is the dominant one (about 60% of the cost). For larger SMES units (>50 MWh), the structural support cost is the dominant one (about 65% of the cost).

There are two coil designs being considered for SMES units, the toroidal design and the solenoid. Solenoid coils use less superconducting material, but their associated electro-magnetic fields cover a larger area than those associated with the toroidal coils. Solenoid coils have been the major focus of most previous development work in the U.S. Large, modular toroidal coils may be four to five times more expensive^[5] (two to five times more superconducting material and as a result, more structural support as well) but they have reduced external electro-magnetic fields and are favored by some project developers, especially outside the United States^[82]. For the purposes of this analysis, we have assumed a solenoid coil design.

Power Conditioning System Costs. The power conditioning system (PCS) cost dominates the capital cost in SMES systems in the 1 MW/1 MW-sec class, is a major component in the larger cold-supported SMES units, and is a relatively small component in the 1000 MW/4000 MWh class earth-supported SMES units. Future advances in power conditioning technology are expected as a result of developments in the areas of devices, device packaging, and power integrated circuits. These advances should help reduce the PCS cost to more attractive levels, especially for the applications where the PCS cost is the dominant one (low storage capacity cold-supported SMES).

Contingencies. Assumptions for the SMES contingencies are based on discussions with the two ETM contractors^[174.4,174.5] and on contingencies typically used with other technologies (e.g., Pumped Hydro, Pulverized Coal)^[144]. The contingencies assumed for the different SMES sizes are shown in Exhibit 4-2. Contingencies for the coil/refrigeration cost component of earth-supported SMES systems are assumed to be 20% of the cost. For cold-supported systems, the contingencies for the coil/refrigeration cost component are assumed to be 10% of the cost. The contingencies for the PCS cost component are assumed to be 5% of PCS cost. The PCS contingency is low because these systems are commercially available. The contingencies for the cold-supported system are lower than those for the earth-supported system since site labor, materials, and construction costs are reduced in the case of a cold-supported system.

Interest During Construction. Interest during construction on the costs already incurred is accounted for by utilities as Allowance for Funds Used During Construction (AFUDC). The magnitude of AFUDC is determined by the length of the construction period and the interest rates for construction financing. Since the PCS would not be a long lead time component and would not be required to be on-site a long time in advance, an AFUDC of 5% of the PCS cost is used. Since the earth-supported coil/refrigeration systems, site work, and construction require longer lead time, an AFUDC of 15% is used for earth-supported systems. For cold-supported SMES systems, an AFUDC of 6% is used for the coil/refrigeration system because of the shorter construction times associated with the cold-supported versus the earth-supported SMES. For cold-supported SMES units, the equivalent of AFUDC would most likely be included in the FOB price of the equipment.

4.2 Assessment of SMES Capital Costs for Near Term Installation (Year 2000)

4.2.1 Earth-Supported SMES Systems

The base cost estimates (without contingency and AFUDC) for SMES component systems are shown in Exhibits 4-4 and 4-5. Exhibit 4-4 shows the coil/refrigeration system costs and Exhibit 4-5 the costs for the PCS. The coil/refrigeration costs of Exhibit 4-4 are in general agreement with the data from the ETM cost estimates^[91]. The coil/refrigeration cost curve changes as it moves from cold-supported to earth-supported systems (at about 20 MWh). The PCS cost estimates of Exhibit 4-5 are also in general agreement with the data from the ETM cost estimates^[91] as well as with data for PCS costs associated with other storage technologies.^[42,43,44,84,86,87]

The total capital cost of SMES units, including AFUDC and contingency, in \$/kW versus the power capacity of the units is presented in Exhibit 4-6 for typical storage times of 3 mins (e.g., most transmission applications), 2 hours and 10 hours (e.g., for generation diurnal storage applications). These storage capacities bracket the ranges of interest to utilities. Certain utilities may favor 4-5 hours of storage. Costs for these systems can be developed from the relationships used to develop these results.

4.2.2 Cold-Supported SMES Systems

The capital cost estimates for cold-supported SMES units (<20 MWh) are based on data for earth-supported systems reduced by an average factor of 20% to account for the reduced structural support. The reduction factor between earth-supported and cold-supported systems is based on data from various sources^[8,91]. The total capital cost depends to a large extent on the PCS cost, especially for units with high power capacity and low energy storage capacity.

Exhibit 4-4 Estimated SMES Col/Refrigeration Capital Cost (Year 2000, \$1992)

Exhibit 4-5 Estimated PCS Capital Cost for SMES Units (Year 2000, \$1992)

Exhibit 4-6 SMES Total Capital Cost for Various Storage Times (Year 2000, \$ 1992)

4.2.3 Cold-Supported SMES Systems (1 MW/1 MW-sec)

The cost for SMES units in the 1 MW/1 MW-sec class is expected to be \$500/kVA based on information for current commercial units of 2 MW or smaller^[3,174,3]. Typical units are in the 50 kW to 1 MW size range with a time of discharge of 1-30 seconds at full power. As already stated, the cost is driven by the PCS cost which becomes the dominant component for SMES systems with high power capacity and small energy storage capacity.

4.3 Assessment of SMES Capital Costs for Future Commercial Installations (Year 2030)

4.3.1 Earth-Supported SMES Systems

The cost of SMES systems is expected to decline as the technology is commercialized, technology improvements are implemented, and manufacturing experience accumulates.² It is assumed that the cost reduction due to all these

² Realizing that capital cost estimates typically increase as a technology approaches commercialization and more becomes known about the technology, and then rapidly decrease as succeeding versions of the technology are optimized.

factors will be about 50% from the base case capital cost (first of a kind cost for the year 2000). This cost reduction assumes a 15% reduction to account for the maturing of the technology and a 35% reduction to account for technological breakthroughs. This type of learning curve effect is commonly used in technology forecasting in which past and current experience is fed-back into future designs. These overall cost reductions are comparable to learning curve effects of 85% over five generations, or 90% over 7 generations.³ Although the estimates of capital cost reduction as the technology matures are somewhat subjective, they are consistent with estimates developed for the ETM^[89,174,4], and are similar to the cost reduction realized with other power-generation-related technologies.^[148]

4.3.2 Cold-Supported SMES Systems

Costs for cold-supported SMES systems are assumed to follow similar reductions as for the large earth-supported systems. It is assumed that there would be a cost reduction due to technology improvements and breakthroughs of about 50% from the baseline capital cost (first of a kind cost for the year 2000). Exhibit 4-7 shows the effect of technology maturity and technology improvements on SMES total capital cost.

4.3.3 Cold-Supported SMES Systems (1 MW/1 MW-sec)

The SMES system cost for 1 MW/1 MW-sec class units is expected to reach \$250/kVA through the reduction of PCS costs, use of high-temperature material, manufacturing cost reductions and technological improvements. Future significant advances in power conditioning technology are expected as a result of developments in the areas of devices, device packaging, and power integrated circuits. These advances should help reduce PCS cost, which will have a major impact on those SMES applications where the PCS cost is the dominant one.

4.4 Projections of Total Revenue Requirements for SMES

The revenue requirements for a generation resource is the amount of money that must be collected from customers to compensate a utility for all expenditures in capital, goods, and services associated with the implementation of the resource addition. The revenue requirement is equal to the capital carrying charges plus operating and maintenance expenses.

³ That is, total capital cost for each succeeding generation of technology is 85%-90% of that for the previous generation of technology—a reasonable value for technology of this type.

**Exhibit 4-7 Fully Commercialized Future Installations—SMES Total Capital Cost
(Year 2030, \$ 1992)**

4.4.1 Revenue Requirements for SMES Based on Energy Storage

The total annual cost for a SMES system includes a capital cost component, a fixed and a variable operating and maintenance cost, the cost of refrigeration energy, and the cost of off-peak electricity (adjusted for losses) to charge the SMES unit.

The capital cost component is based on the total capital cost which is converted into an annual capital charge by accounting for depreciation, capital (equity) charges, interest charges, taxes and insurance, and income taxes, consistent with standard utility revenue requirements methodology. The capital cost component of the SMES system used in screening curves for high storage generation cost comparison is based on a storage system sized for daily operation. This means, for example, that for a capacity factor of 2 hours/24 hours (2 hours operation per day), a 1000 MW SMES system is sized with 2000 MWh of storage to determine the generation cost, while for a capacity factor of 4/24, a 1000 MW SMES system is sized with 4000 MWh of storage to determine the generation cost. This sizing provides the system with adequate capacity to provide the required energy without recharging for the duration of one day. This approach to sizing the SMES means generation costs drop more

slowly as the capacity factor increases (as opposed to less storage capacity with multiple chargings daily), however, it is consistent with diurnal storage applications.

For the operation and maintenance (O&M) costs, data from comparable storage technologies (e.g., batteries, pumped hydro) was adjusted and used, along with separate estimates for refrigeration power. This information was developed from data in the EPRI-TAG^[144] (Technical Assessment Guide) and historic power plant data.^[188] The fixed O&M is estimated to be \$5/kW-yr for cold-supported SMES units (<20 MWh) and \$10/kW-yr for earth-supported units greater than 20 MWh. The variable O&M (not including cost of charging electricity) is estimated to be 1.0¢/kWh for cold-supported SMES units and 0.5¢/kWh for earth-supported SMES units. The off-peak electricity cost required to charge a SMES unit was based on DOE/EIA projections for the U.S. electric power through the year 2010^[142]. Only the energy component of the electricity price is used in the calculations, consistent with bulk off-peak power pricing practices. It is assumed that the off-peak electricity cost would be further reduced by 25% to account for bulk power cost savings. For electricity prices beyond the year 2010, it is assumed that associated fuel prices will escalate at a constant real rate of 1.1% (based on natural gas as fuel). The electricity costs used are 1.8¢/kWh for the year 2000 and 2.8¢/kWh for the year 2030 (see Exhibit 4-8). For refrigeration energy costs, average electricity prices are used, since refrigeration will be a continuous, 24 hour/day, expense. In real terms, the average price for electricity is projected to be fairly constant through the year 2010. We have continued this pattern through to the year 2030.

Exhibit 4-8 Electricity and Fuel Costs Assumptions (1992 dollars)

Year	2000	2010	2030
Off-peak Electricity Cost, ¢/kWh ⁽¹⁾	1.80	2.26	2.80
Refrigeration Energy Cost, ¢/kWh ⁽²⁾	6.8	6.9	7.1
Natural Gas Cost, \$/MMBtu	3.28	5.64	7.01
Coal Cost, \$/MMBtu	1.85	2.17	2.65
Oil Cost, \$/MMBtu	4.78	6.20	7.57

(1) Off-peak electricity cost is based on the fuel cost component of the Electricity Cost only. This cost is further reduced by 25% to account for the off-peak rate reduction.

(2) Based on average electricity price projections.

Source: [142] figures adjusted for \$ 1992

4.5 Cost of Competing Technologies

The economic analysis compares SMES units with competing technologies for the years 2000 and 2030 over varying sizes to reflect a wide range of applications. Storage technologies, (e.g., pumped hydro), generation technologies (e.g., gas turbines), and electrical technologies (e.g., static VAR compensators) are all considered in the analysis.

4.5.1 Generation Applications

The competing technologies evaluated for generation applications include:

- Conventional pumped hydro energy storage plant (3 x 350 MW),
- Compressed air energy storage (CAES 100 MW),
- Simple gas turbine (GT 200 MW),
- SMES (1000 MW).

The cost-performance assumptions used for these technologies for the economic analysis are tabulated in Exhibit 4-9. The electricity cost assumptions were summarized in Exhibit 4-8.

The natural gas price is estimated to be \$3.28/MMBtu in the year 2000^[142]. For the year 2030, the natural gas price is estimated to be \$6.98/MMBtu based on a constant real escalation of 1.1% per year after the year 2010.

Exhibit 4-9 Cost/Performance Assumptions for Competing Generation Technologies¹

Technology	Lead-Acid Battery	Simple Cycle Gas Turbine	Simple Cycle Gas Turbine	Compressed Air Energy Storage	Pumped Hydro Energy Storage	SMES	
						Cold-Supported	Earth-Supported
Plant Size (no. of units x unit size, MW)	1 x 20	1 x 20	1 x 200	1 x 100	3 x 350	<20 MWh	>20 MWh
Storage Size, hours	5	N/A	N/A	10	10	0-3 min	1-10 hr
Capital Cost, \$/kW (\$1992)	969	715	400	642	1154	see Exhibit 4-6	
O&M Fixed, \$/kW-yr	1.55	6	6	2.5	4.2	5.0	10.0
O&M Variable, ¢/kWh	0.72	0.6	0.6	0.21	0.42	1.0	0.5
Energy Requirements (kWh Input/kWh Output) ²	1.31	2.72	2.49	0.76 + 4000 Btu Fuel	1.36	1.05	1.05

(1) Technology assumptions are derived from the Arthur D. Little power generation technology database.

(2) Turnaround Efficiency

4.5.2 Transmission and Distribution System Applications

The competing technologies evaluated for transmission and distribution applications requiring storage (typically 1 hour to 5 hours) include:

- Lead-Acid Battery energy storage (20 MW - 5 MWh)
- Simple Cycle Gas Turbine (GT 20 MW)
- SMES (20 MW - 1 MWh)

The fuel and electricity cost assumptions were summarized in Exhibit 4-8. The cost and performance assumptions for these technologies are summarized in Exhibit 4-10.

Exhibit 4-10 Cost/Performance Assumptions for Transmission Applications (Storage)¹

Technology	Power Capacity (MW)	Storage Size (hours)	Efficiency (%)	O&M Cost (\$000/yr)	Storage Capital Cost (\$/kWh)	Total Capital Cost	
						(\$ million)	(\$/kW)
Lead-Acid Batteries	20	5	76	283	172	19.4	969
SMES ²	20	0.05	95	256 ³	47,500	51.9	2,597
Simple Cycle Gas Turbine	20	N/A	40	330	N/A	8	400

(1) Technology assumptions are derived from the Arthur D. Little power generation technology database.

(2) Costs are based on a load factor of 0.2, SMES recharge 4x/day

(3) SMES O&M costs are assumed to include refrigeration energy costs.

The competing technologies evaluated for dynamic transmission and distribution applications that require only small amounts of real power (i.e., small storage requirements) include:

- Lead-acid battery,
- Advanced flywheel systems,
- Electrochemical capacitor systems, and
- SMES

The cost and performance assumptions used for batteries and SMES are found in Exhibit 4-11.

For small energy storage systems, normalizing economics on the basis of kWh storage is awkward and may be misleading. Since the benefits in these applications are usually event driven (with very short duration - from ½ cycle to 3 seconds), normalizing by consumption is unreasonable (2 events per shift, of 1 cycle duration, constitute about one-half minute of actual usage per year) and costs were normalized to \$/year instead for these applications.

Exhibit 4-11 Cost/Performance Assumptions for Transmission Applications (Dynamic)

Technology	Power Capacity (MW)	Storage Size (sec)		Effective Efficiency ⁽²⁾ (%)	O&M Cost (\$million/yr)	Capital Cost	
		sec	MW-sec ⁽¹⁾			\$ million	\$/kW
Lead-Acid Batteries (Year 2000)	500	100	500	70 - 75	3.0 ⁽³⁾	35.5	71
SMES (Year 2000)	500	1	500	85 - 90	0.8 ⁽⁴⁾	60.0	120
Lead-Acid Batteries (Year 2030)	500	75	500	70 - 75	3.0 ⁽³⁾	18.5	37
SMES (Year 2030)	500	1	500	85 - 90	0.8 ⁽⁴⁾	30.0	60

- (1) Based on available discharge assume 1% depth of discharge for batteries 100% depth of discharge for SMES
(2) Effective efficiency is equal to delivery efficiency divided by base loaded charging plant efficiency⁽⁸⁸⁾
(3) Includes replacement cost
(4) Includes refrigeration energy cost

4.5.3 Customer Service Applications

Most customer service applications focus on prevention of power interruptions and power quality enhancement. The benefits associated with these applications lie in the avoidance of costs associated with downtime of equipment due to power interruptions, equipment protection, and the value of the equipment should it fail. The SMES technology (2 MW/2 MW-sec) is compared with competing technologies including batteries, advanced flywheels, and electrochemical capacitor. The cost and performance assumptions used for these technologies are found in Exhibit 4-12.

Exhibit 4-12 Technology Comparison for Customer Service Applications⁽¹⁾

Technology	Typical Size		Total Capital Cost (\$000)	Storage Cost (\$000/kWh)	O&M Cost (\$000/Yr)	Replacement Cost Issues	Cycle Life
	Power (MW)	Storage (kWh)					
Batteries	2	6	500	17	15	\$33,000/ every 5 yrs	30,000
SMES	2	0.6	1,000	900	68 ⁽²⁾	minimal	no limit
Advanced Flywheel	2	15	700	10	<15	minimal	no limit
Electrochemical Capacitors	2	6	65	17	<15	minimal	150,000

- (1) Technologies compared can provide a minimum 2 MVA capacity for a minimum of 2 seconds
(2) Includes refrigeration energy costs

5.0 Generation Applications

5.1 Generation Market Segment Definition

The generation segment of the electric utility industry produces electrical energy from a primary form of energy - gas, oil, coal, hydro, nuclear, etc. The electricity generated (bulk power) is delivered to an electrical transmission system, which in turn feeds local electrical distribution systems, which supply power to electric customers. Major objectives of the electric generation segment are to have adequate reliable capability available to meet the constantly varying demand for electricity, and to generate electricity at the lowest possible economic cost.

Power generation requirements can be met by traditional supply-side resources or by demand-side management. Traditional supply resources such as gas turbines can be owned by the local utility, or more recently, by non-utility generators (NUGs). An alternative to traditional supply side resources is the use of demand management techniques. Demand management strives to favorably influence a customer's demand for electricity to obviate the need for additional generation capacity, ideally at costs substantially lower than the incremental cost of electricity. Demand side management (DSM) techniques do not directly compete with SMES and have been excluded as a generic technology from this analysis.

Demand for electricity, and hence the requirement on the generation segment, varies constantly, from instantaneous changes, to daily cycles, and seasonal variations. Daily demand variation may be as extreme as a factor 2 change from the mid-day peak to the late-night minimum load. Utilities meet this constantly changing demand with an economic mix of different types of generation:

- **base loaded capacity:** the lowest cost generation (\$/MWh), typically operates 24 hours per day with some day-to-night turndown, typically averaging 60%-65% capacity factor⁴ over the course of a year.
- **intermediate capacity:** medium cost generation (\$/MWh), typically operates 24 hours per day during high demand seasons, may be shut down nights, weekends, or longer during low demand seasons, typical annual capacity factors of 30%-40%.
- **peaking capacity:** high cost generation (\$/MWh) used to supplement generation during periods of peak demand, may operate 1-4 hours per day during peak seasonal periods with 200-500 hours of total operation per year, 3-5% annual capacity factors are not unusual.

In addition to generation technologies, utilities can also meet electricity demand through the use of storage. Because of the difference between daytime and nighttime demand and the difference in generation cost to meet peak versus base needs, utilities are very interested in economic storage technologies which would allow them to

⁴actual generation divided by potential generation at 100% capacity full time

generate low cost power at night, store it, and then discharge the power during peak daytime demand periods. This application of storage is referred to as diurnal storage.

Emerging storage technologies such as SMES, Compressed Air Energy Storage (CAES), or lead-acid batteries will compete with traditional pumped hydro storage in this application. Storage technologies give utilities flexibility to operate their baseload capacity more efficiently, while eliminating the need for operation of, and investment in, less efficient peaking capacity.

5.2 Utility Generation Problems and Needs

Within the generation market segment utilities are currently facing a variety of problems in the generation of bulk power for delivery to the transmission and distribution grids. Based on a review of utility system needs and interviews with system and generation planners at over 18 utilities, six different problems, from an original list of over 15, were ranked to understand the relative importance of each one. The most pressing generation problems facing utilities include:

- Inadequate peak power supply,
- Improve load following capability,
- Reduce peak cost via storage,
- Integrate bulk power transfers,
- Inadequate spinning reserve, and
- Automatic Generation Control.

Based on an analysis of the results of our utility interviews, we have ranked the importance of each of these problem categories. The Generation Problem Matrix, Exhibit 5-1, summarizes the results of this analysis. The two lowest ranked problems, which were inadequate spinning reserve and the need for Automatic Generation Control (AGC), were broken out separately in this comparison due to their frequent reference as a potential benefit for SMES systems. Because these two problems were not identified as significant problems by the utilities we interviewed, they have been dropped from our analysis. As will be discussed later, spinning reserve is frequently an additional benefit obtained when providing improved load following capability. AGC is frequently an additional benefit obtained when solving the problem of integration of NUG generation and power transfers from outside a utility's service territory.

Exhibit 5-1 Generation Problem Matrix

GENERATION PROBLEMS

WHATs vs. HOWs

Serious Problem/Need	●●●
Average Problem/Need	●●○
Minor Problem/Need	●○○

	WEIGHT	Inadequate Peak Power Supply	Reduce Peak Cost	Need for Improved Load-Following	Integrate Bulk Transfers	Inadequate Spinning Reserve	Automatic Generation Control
Utility #1	2	●	○	○	○	○	○
Utility #2	1	○	○	○	○	○	○
Utility #3	3	●	○	○	○	○	○
Utility #4	2	○	○	○	○	○	○
Utility #5	1	○	○	○	○	○	○
Utility #6	1	○	○	○	○	○	○
Utility #7	2	○	○	○	○	○	○
Utility #8	2	○	○	○	○	○	○
Utility #9	2	○	○	○	○	○	○
Utility #10	3	○	○	○	○	○	○
Utility #11	2	○	○	○	○	○	○
Utility #12	1	○	○	○	○	○	○
Utility #13	2	○	○	○	○	○	○
Utility #14	1	○	○	○	○	○	○
Utility #15	1	○	○	○	○	○	○
Utility #16	1	○	○	○	○	○	○
Utility #17	1	○	○	○	○	○	○
Weighted Total		182	132	168	134	112	76
Rank		1	4	2	3	5	6

5.2.1 Inadequate Peak Power Supply

Insufficient peak power capacity is the highest priority problem facing electric utilities over the next decade or more. Many utilities currently have adequate or even excess amounts of base and intermediate load capacity in the form of nuclear and coal, oil and gas fired thermal capacity, gas turbine combined cycle systems and NUGs. Actual reserve margins (the amount of excess capacity needed to ensure reliability) for many utilities are 30-35%; with minimum required reserve margins often being 20% or lower, it will be several years before the need arises for significant amounts of new baseload capacity. Many utilities do not foresee major needs for base load capacity until the year 2010 or later.

However, many utilities are lacking resources which could be used for peaking over the next 10 to 15 years. Additional peaking capacity is needed to provide proper system flexibility and improve overall system efficiency. A major reliability concern which has been expressed by NERC is the dependability of DSM over the long-term and its availability during peak demand periods. This concern applies to almost all of the NERC regions, although it may be most prevalent in the Northeast and California where more significant amounts of DSM are being pursued. If DSM is less dependable than expected, there may be an even greater need for peaking capacity than currently is anticipated.

Characteristics of technologies or solutions which are desirable for peaking capacity include:

- high availability and reliability,
- modularity,
- siting ease.

Low forced outage rates and high mean time between overhauls will contribute to high availability. The need to match demand more precisely with supply has led to a need for technologies to be modular, allowing staged additions of capacity over several years. Increased difficulty over the last several years in obtaining regulatory approval for large capacity increments and the associated large capital expenditures has led utilities to increase their focus on modular capacity technologies. Modularity also allows technologies to be sited in a variety of locations within the service territory.

5.2.2 Improved Load Following Ability

The dynamic issues associated with load following capability were of significant interest to many utilities, but were of less importance than peak power supply needs. In general there is a need to be able to respond more effectively to instantaneous changes in load. A generation unit's ability to respond can depend on whether or not the unit output is increasing or decreasing and what the relative unit load is. A few utilities expressed concerns about baseload capacity being slow to respond to load variation changes which makes this capacity unable to support these needs. Heat rate

fluctuations caused by cycling baseload capacity can also be decreased by using other technologies to perform load following. In the future with increasingly open transmission access, and increased reliance on bulk power transfers, it is expected that there will be increased need for generation which will closely follow load swings. In general it is felt that many technologies which are currently available may be used to fill these needs.

Desirable attributes of technologies or solutions for load following problems include:

- accurate ramp rate control,
- good part load efficiency, and
- cycling capability.

The ability to match rate of load change over time helps to maintain system stability and can reduce the cycling requirements of other generation units. This will in turn allow base and intermediate load units to run at more efficient performance points. The ability to operate at part load in either a steady state or cycling mode at high part load efficiencies (low heat rates) is another important attribute for these technologies. Additional benefits of reduced cycling of thermal units will be reductions in scheduled maintenance and increased useful life.

5.2.3 Reduce Peak Energy Production Cost

The need to reduce peak energy production cost (i.e., via storage) was of lesser importance in general, being more of a regional concern. Utilities which have significant differences in peak and off-peak power generation costs will benefit most from storage. Many utilities we talked to indicated that they cannot justify investments in storage resources due to relatively small differences in the marginal cost of electricity between peak and off-peak. Utilities with significant amounts of nuclear or baseload hydro capacity may benefit most from storage. Very little conventional pumped hydro storage is planned by utilities over the next ten years. According to NERC, approximately 1,600 MW will be added by utilities. An additional 5000 MW or so of pumped hydro storage may be added by non-utility generators.

In areas such as Florida where there are few adequate sites available for pumped hydro storage, there is an interest in alternative storage technologies. There is a concern among many utilities that environmental regulations regarding the flow of water for recreational use and fisheries will make siting new pumped hydro facilities more difficult. A few utilities have pumped storage capacity which will meet their needs adequately in the near term. Longer term (beyond 10 years), the need for storage may increase. There is also a desire to locate storage technologies closer to the load centers in the future to reduce transmission and distribution costs and to facilitate control. This will favor smaller, modular increments of storage capacity.

Desirable attributes of technologies which will reduce peak energy production cost include:

- high turnaround efficiency,
- high storage efficiency or low losses,
- operating range flexibility,
- modularity, and
- siting ease.

The efficiency of an energy storage technology is dependent on the energy transfer mechanism, the operating requirements and any leakage which occurs while the energy is stored (e.g., of compressed air for CAES, of reservoir water for pumped hydro). The energy transfer mechanism for SMES consists of the power conditioning system (PCS) and the AC/DC inverter. For pumped hydro the equivalent would be the reversible pump and motor/generator. These devices control the turn-around efficiency. SMES has an operating requirement for refrigeration, which decreases the storage efficiency. Hydro should have little leakage, whereas compressed air may have fairly substantial leakage. Operating flexibility has to do with the technology's ability to perform effectively at varying loads and operating times. Modularity and siting issues are similar to those discussed above under peak power supply.

5.2.4 Integrate Bulk Power Transfers

Concerns were raised by some utilities regarding the integration of NUGs into their systems and the problems associated with transfer of power in from other regions. Many of the concerns over the integration of power are related to power quality issues, and are more of a transmission and distribution (T&D) concern. These concerns will be discussed separately in Section 6. Issues which are addressed as a generation problem have to do with the integration of capacity. Many NUGs are located far from the utility load centers and instability may arise due to trips or interruptions. From the generation perspective, the utilities are anticipating that NUGs will be of increasing concern, as cost competition with power from NUGs in a retail wheeling market becomes more prevalent. Providing adequate ability to control power provided by NUGs and transfers of power from outside the general service territory are becoming more important problems.

Desirable attributes of technologies which can help to solve problems of integration of NUG capacity and transfers include:

- providing automatic generation control,
- frequency regulation, and
- storage to facilitate transfers.

Automatic generation control (AGC), pertains to a technology's ability to respond to fast load changes, loss of generation capacity and failures in the transmission system which can cause a response from the generating machinery. Storage in a system can help to maintain frequency in response to minor load variations and minimize power

quality problems. As utilities move more towards a service orientation, power quality improvements will become a more critical aspect of their business. Energy storage can also help to control the coordination of power transfers from outside the region. Storage capability coupled with power electronics, which will provide reactive power without capacitors, and modularity are viewed as key technical characteristics which will help utilities address this concern.

5.3 Evaluation Criteria

In order to define how well potential solutions will satisfy utility generation problems, we developed a list of prioritized criteria used in utility decision making. A preliminary list of criteria was refined using a series of utility interviews to a) prioritize the criteria (high/medium/low), b) add additional criteria, and c) delete unnecessary criteria. The criteria have been grouped into five major categories: technical performance, economic, environmental issues, risk and an "other" category for construction lead time. The Generation Criteria Matrix (Exhibit 5-2), is a summary of the survey results regarding the importance of the evaluation criteria. The final weightings used in evaluating generation solutions are:

- technical performance - 35%
- economic characteristics - 30%
- environmental issues - 20%
- risk - 11%
- other (construction time) - 4%

5.3.1 Technical Performance

Technical performance is an overall measurement of the adequacy of the candidate solutions in meeting the technical or performance requirements of the utility. Utilities weight technical performance as a key evaluation characteristic for generation problems as it relates directly to the problem or need the utility is trying to satisfy. For generation problems, technical performance is relatively straight forward and measures the ability to effectively deliver electricity (via generation or storage). Related technical performance issues include reliability/availability, modularity/site flexibility and full and part load efficiency.

Exhibit 5-2 Generation Criteria Matrix

GENERATION CRITERIA

WHATs vs. HOWs

Very Important	●●●
Important	●●
Not Important	○

	WEIGHT	TECHNICAL PERFORMANCE	ECONOMIC	Revenue Requirements	Capital Costs	O&M Cost	System Efficiency	Environmental Externalities	ENVIRONMENTAL ISSUES	EMF	Air Quality	Solid Waste Disposal	Size/weight	Water quality, usage	Audible Noise	RISK	Technical Maturity/Support	Regulatory Approval	OTHER	Construction lead time
Utility #1	2	●	●	●	●	●	●	○	●	●	●	●	○	●	○	●	●	●	●	○
Utility #2	1	●	●	●	●	●	●	○	●	●	●	●	○	●	○	●	●	●	●	○
Utility #3	3	●	●	●	●	●	●	○	●	●	●	●	○	●	○	●	●	●	●	○
Utility #4	2	●	●	●	●	●	●	○	●	●	●	●	○	●	○	●	●	●	●	○
Utility #5	1	●	●	●	●	●	●	○	●	●	●	●	○	●	○	●	●	●	●	○
Utility #6	1	●	●	●	●	●	●	○	●	●	●	●	○	●	○	●	●	●	●	○
Utility #7	2	●	●	●	●	●	●	○	●	●	●	●	○	●	○	●	●	●	●	○
Utility #8	2	●	●	●	●	●	●	○	●	●	●	●	○	●	○	●	●	●	●	○
Utility #9	2	●	●	●	●	●	●	○	●	●	●	●	○	●	○	●	●	●	●	○
Utility #10	3	●	●	●	●	●	●	○	●	●	●	●	○	●	○	●	●	●	●	○
Utility #11	2	●	●	●	●	●	●	○	●	●	●	●	○	●	○	●	●	●	●	○
Utility #12	1	●	●	●	●	●	●	○	●	●	●	●	○	●	○	●	●	●	●	○
Utility #13	2	●	●	●	●	●	●	○	●	●	●	●	○	●	○	●	●	●	●	○
Utility #14	1	●	●	●	●	●	●	○	●	●	●	●	○	●	○	●	●	●	●	○
Utility #15	1	●	●	●	●	●	●	○	●	●	●	●	○	●	○	●	●	●	●	○
Utility #16	1	●	●	●	●	●	●	○	●	●	●	●	○	●	○	●	●	●	●	○
Utility #17	1	●	●	●	●	●	●	○	●	●	●	●	○	●	○	●	●	●	●	○
Weighted Total		252		244	248	228	220	74		228	230	174	40	114	48		200	178		164
Rank		1	1	3	2	5	7	13		5	4	10	15	12	14		8	9		11

5.3.2 Economics

Economics were found to be the second most important characteristic used by utilities to screen generation technologies. When making resource decisions, utilities are generally required to choose the resource option with the lowest cost over the life cycle of the asset. Generation planners typically use "least cost planning" (LCP) techniques to make these decisions regarding the lowest cost resource option. The economic criteria considered in our review include:

- *Revenue requirements* - This is the levelized net present value of the life-cycle costs of the option over its useful life.
- *Capital costs* - Includes all equipment, construction, labor, contingencies, and any necessary allowances for funds used during construction (AFUDC).
- *Operating and maintenance costs* - Includes any non-fuel operating costs and allowances for planned maintenance.
- *System efficiency* - The heat rate for generation options and the turn around and storage efficiency for storage technologies.
- *Environmental externalities* - Monetized values for accounting for the impact environmental emissions have on the cost of resource options. This accounting varies regionally and is expected to weigh more heavily in the future.

Revenue requirements are seen by utilities as the most critical economic criteria currently used to evaluate the economics of competing technologies. Revenue requirements are a measure of the lifetime cost of the asset including capital investment, operating and maintenance costs, fuel costs, and financial costs including depreciation, taxes and insurance, income taxes, and allowance return on equity capital. Capital costs, operating and maintenance costs (O&M), and system efficiency are also viewed by some utilities as being important criteria on their own. Since all of these parameters contribute to the determination of revenue requirements the relative weighting among them does not significantly impact the ultimate economic ranking.

An important consideration for the future is the potential impact retail competition may have on economic criteria used for technology selection. As retail competition expands, utilities will need to aggressively focus on being low cost producers of power in order to compete with other power suppliers such as Independent Power Producers (IPPs), other utilities, etc. In the current operating environment, once the lowest cost resource options are identified, utilities focus on low variable cost which determines the dispatch order of their generation capacity. With retail access to transmission systems, this implicit priority may change from minimizing variable costs to minimizing capital costs.

The monetization of environmental externalities is not currently viewed as a critical economic criteria by most utilities. Many utilities are not currently required to factor externalities into their economic evaluations when making resource investment plans. It is generally agreed, however, that in the future this will become a more important issue in the economic assessment of generation options.

5.3.3 Environmental Issues

Environmental issues are increasingly important aspects of generation decision making. Relevant environmental issues for generation include air quality, electro-magnetic fields (EMF) and solid waste disposal. The importance of these issues varies widely depending on regional requirements and specific site issues. Issues considered in our analysis include:

- Electro-magnetic fields (EMF),
- Air quality,
- Solid waste disposal,
- Water usage/quality, and
- Audible noise.

Air quality is by far the most critical environmental issue facing utilities. Emissions from power plants are tightly regulated. The Clean Air Act and its Amendments (CAAA) create limits for SO₂ emissions from power generating plants. More stringent state and regional limits typically apply to other air emissions such as NO_x. Complying with the SO₂ emission limits of the Clean Air Act is the most important air quality concern of utilities, followed by NO_x. Future concerns regarding CO₂ and "ozone" gases may become an issue as well. Increased air quality concerns will put more emphasis on increasing system efficiency and decreasing the use of fossil fuels. Possible requirements to consider environmental dispatch to limit emissions of SO₂ and NO_x (and possibly "ozone" gases and carbon dioxide constraints in the future) may give air quality effects even more influence on generation technology decisions.

EMF is becoming an extremely important issue for utilities due to public perceptions and fears regarding health effects. Electro-magnetic fields surround any electrical conductor. Uncertainty currently surrounds the relative importance of EMF, or the determination of safe levels. AC fields are thought to be worse than DC fields. Whether proven or not, current public opposition is creating significant problems for siting transmission lines and substations leading to delays and cancellations in several proposed projects. Since most new generating facilities also require new or upgraded transmission or distribution lines, the EMF associated with transmission and distribution can influence generation decisions. However, the EMF issue is not currently a direct issue for new generation resources.

Solid waste disposal and water quality are also of concern to utilities, but of less importance than air quality or EMF. Solid waste includes ash and used lubricating and cleaning fluids and any chemicals used in the power plants. Disposal of any of this waste material has become an increasingly important problem. Discharges into cooling water and thermal emissions from power plants are also regulated. In general this is not a difficult problem to overcome, but it adds expense. In most instances, noise and size/weight were not much of a concern, unless the unit would be located near a distribution or feeder system substation where land availability may be an issue or in areas where noise reduction techniques such as enclosures might be required (e.g. near residential areas).

5.3.4 Risk

The perceived risk associated with technology choices is dependent on the experience base of the observer. The electric utility industry generally favors relatively low levels of risk. To a large extent, well known or demonstrated technologies will receive more favorable acceptance due to lower perceived levels of risk. For this evaluation we have divided the risk category into two parts:

- Technical maturity/product support, and
- Regulatory approval.

The maturity of the technology and the credibility of the vendor or supplier is a measure of the likelihood that the equipment will perform as designed for its expected life. Technical maturity of a technology is very important to utilities. Demonstration projects and actual operating experience with a technology are considered very important. Utilities with strong R&D programs are less concerned about technical maturity risks. Many utilities contacted indicated they are not interested in using a demonstration technology, they want to use only commercialized technologies. This would apply to applications of SMES. If, however, an emerging technology has operating characteristics similar to an established technology, this reduces the perceived risk and increases the likelihood of acceptance.

The issue of regulatory approval of new technologies is viewed as being of medium to high concern by utilities. Some utilities expressed more concern than others about having difficulty with the Public Utility Commissions (PUCs) in their State. The familiarity of regulators with a technology and the ease of approval which can be anticipated will help to remove uncertainty associated with planning and siting requirements for a new technology. Regulations tend to drive technology decisions rather than restrain them. Regulators tend to be more critical of technologies they have not had experience with. For many regulatory agencies there is a need to show that a technology has the highest benefit/cost ratio of the available alternatives.

5.3.5 Other Issues

The most significant other issue which was determined to be of importance to utilities in making generation addition plans centered around the construction lead time requirements. This is the planning horizon required for a technology, including licensing, siting requirements, design, and construction time required. Construction lead time is of medium concern to utilities. Typically a utility wants no more than 2-4 years of construction lead time from project approval to commercial operation (including licensing). Some utilities, did state that 5-7 years could be acceptable. In general there is a trend toward smaller capacity increments which may be more well matched to demand growth. This decreases the uncertainty associated with long range planning but requires shorter lead times for new generation capacity. Based on the increased complexity of the planning process and uncertainties associated with demand increases, regulatory approvals and public opposition to projects, it is

generally agreed that shortened lead times will become increasingly important for new resource options.

5.4 Generation Technology Comparisons

Based on an initial screening of technologies, a list of ten alternative technologies was developed for comparison. Each of these technologies was compared on a relative basis versus the technical and non-technical criteria defined in the previous sections. Exhibit 5-3 is a comparison of some of the technical, economic, and operational aspects of the technologies considered. Exhibit 5-4, the Generation Technology Competitiveness Matrix, compares the ten alternative technologies against the evaluation criteria.

The economic assessment performed draws on the technology cost information from Section 4.0. Generation technologies are typically compared on a minimum revenue requirements basis. Exhibits 5-5 and 5-6 compare the projected revenue requirements for SMES, gas turbines, pumped hydro, CAES and batteries in the years 2000 and 2030 respectively.

5.4.1 Gas Turbines

Gas turbines are widely deployed in the electric utility industry. A gas turbine generator consists of a fossil fuel-fired turbine coupled to an electric generator. They are characterized by low capital cost and moderate efficiencies simple cycle high efficiencies when used in combined cycle systems. In low load factor peaking applications, the low capital cost of the technology makes it economically very competitive. Environmental concerns are moderate as the usual fuel (gas, diesel oil) produces very low SO₂ emissions, the technology produces low NO_x emissions, and the moderate efficiency with gas as a fuel produces moderate CO₂ emissions. The construction lead time for gas turbines is relatively short and as an established technology, there is relatively low risk. The primary uncertainty with the technology is the expected levels of natural gas prices over the asset's lifetime.

Exhibit 5-3 Generation Technology Characteristics

TECHNOLOGY	STATUS	CAPACITY INCREMENTS	SITE REQUIREMENTS	ENVIRONMENTAL ISSUES	STORAGE CAPACITY	EFFICIENCY	LIFE	CAPITAL COST	CONSTRUCTION TIME	TECHNOLOGY DEVELOPMENTS
PUMPED HYDRO	Mature	>200MW	Limited based on water need	• zero air emissions • water use issues	6-10 hours	70-75% effective (1)	50 years	high ($\pm$ 40%)	5-10 years	Underground pumped hydro
COMPRESSOR AIR ENERGY STORAGE (CAES)	Emerging	>50MW	Somewhat limited - salt, rock, caverns, aquifers	• emission similar to G.T.'s • zero SO ₂ , 9-40PPM NO _x	6-10 hours	80%($\pm$) effective (1) -requires gas turbine	20($\pm$) yrs (limited by GT)	moderate to high	3-5 years	New GT technology
GAS TURBINES	Mature	1-200MW	Flexible	• zero SO ₂ • 9-40 PPM NO _x	N/A	30-38% (HHV) (2)	15-20 years	Low	2-3 years	New GT technology improved efficiency
RECIPS	Mature	<1-20MW	Flexible	• depends on fuel • 40-80 PPM NO _x	N/A	30-38% (HHV) (2)	10-15 years	Moderate	2-3 years	New technology improved efficiency
BATTERIES	Emerging	<1-20MW	Flexible	• zero emissions • disposal issues	3-5 hours	70-75% effective (1)	3-7 years	Low - moderate	1-2 years	Advanced - lower cost - longer life
FLYWHEELS	Future	<1-10MW	Flexible	• zero emissions	3-5 hours	65-75% effective (1)	10-20 years	Moderate - high	1-2 years	New material
SMALL SMES (100MW/20MWh)	Future	100MW/20MWh	Requires moderate site open area	• zero emissions • EMF concerns	10-15 minutes	85-90% effective (1)	30 years	High	3-5 years	Technology breakthrough
LARGE SMES (1000MW/4000MWh)	Future	1000MW/4000MWh	Requires large open area	• zero emissions • EMF concerns	4 hours	90-95% effective (1)	30 years	High	5-10 years	Technology breakthrough
DSM	Emerging	Variable (small)	Requires cooperation of end user	• no environmental concerns	N/A	N/A	uncertain	Low - moderate	Implementation 0-1 years	Conservation technologies
FUEL CELLS	Future - Emerging	<1-20MW	Flexible	• zero SO ₂ • low NO _x	N/A	40-45% (HHV) (2)	15-20 years (5 yr stack replacement)	High	2-3 years	Advanced cycles - high efficiency

(1) Effective efficiency is equal to delivery efficiency divided by base-loaded charging plant efficiency

(2) Higher heating value of fuel used for determination of efficiency.

Exhibit 5-5 Near Term Economics of Generation Alternatives

Exhibit 5-6 Longer Term Economics of Generation Alternatives

5.4.2 Pumped Hydro

Pumped hydro storage systems are in routine service in the electric utility industry, although the total number of installations is relatively small. A pumped hydro system uses a reversible pump/turbine motor/generator system working between an upper and lower water reservoir. During low demand periods, the unit operates as a motor-driven pump to pump water from the lower reservoir to the upper. During peak demand periods, the flow is reversed and the unit operates as a turbine generator to produce electricity as water flows from the upper reservoir to the lower. Because of the low differential heads typically involved, the size of the reservoir required is large. Pumped hydro requires special terrain and costs vary significantly (40%) from site to site. Pumped hydro units usually have relatively high capital costs with significant economics of scale; operating costs are relatively low. Overall economic attractiveness depends upon the availability of low cost off-peak power. Pumped hydro has no air emission per se (although any emissions associated with the generation of off-peak power need to be factored in). Because of the size and nature of the reservoirs required, pumped hydro may have significant land use or siting issues.

5.4.3 CAES

Compressed air energy storage (CAES) is an emerging storage technology which is expected to become widely employed. An electric motor-driven compressor is used to pressurize air in an underground cavern or reservoir during off-peak periods. The stored energy is converted back into electricity by using the combustor/turbine portion of a gas turbine fired on natural gas or distillate fuel. Rock or salt caverns and aquifers are being considered. Potential sites for CAES are thought to exist throughout three-quarters of the U.S. Construction lead times are expected to be similar to that for gas turbines. Cost per kW are expected to be similar to gas turbines due to relatively low costs for storage development and high power output capabilities from gas turbines without compressors. Emissions should be similar to or lower than that for gas turbines, but emissions associated with primary generation of off-peak power should be factored in. Concerns exist regarding the potential leakage of compressed air from storage.

5.4.4 Large SMES

The typical size of large SMES for generation applications would be 1000 MW/4000 MWh. The cost of the energy storage component of this system dominates the cost, making up over 95% of the total. Large systems are characterized by very high efficiencies and low refrigeration energy requirements. Sites will be limited based on requirements for significant areas (several square miles) needed to contain magnetic fields. Concerns exist regarding the human health effects and potential wildlife effects of DC fields. Construction lead times will be moderate to long (5-10 years) due to the size of construction projects. Emissions from SMES plants will be essentially zero, but emissions from primary source of off-peak generation need to be considered.

5.4.5 Battery System

Battery energy storage systems are currently being demonstrated for use in utility applications. The battery plant is composed of modular units configured to provide 3-5 hours of energy storage at the rated conditions. A power converter is used to perform AC/DC inversion and control power input/output. Lead-acid starting/lighting/ignition (SLI) battery technology is available in mature, mass produced automotive and traction products. Battery replacement is typically required every 5-10 years depending on service. Advanced batteries may utilize either the sodium-sulfur or the zinc-bromine system. Actual capacity is determined by cycling requirements and allowable discharge. Battery plant construction lead times are expected to be relatively short due to their modular nature. Capital costs of battery storage component appears to be quite low. Emissions from battery systems will be essentially zero, however, emissions from primary generation should be considered. Battery disposal may be a problem, but there is currently significant interest in recycling.

5.5 Analysis of Generation Alternatives

5.5.1 Inadequate Peak Power Supply

The most important need facing utilities over the next 10-15 years will be for supplying peak power. In Exhibit 5-4, technologies which rank highest for peak power supply are those which generate power as opposed to supplying power from stored energy. Modularity and siting flexibility are valued characteristics in the comparison of potential solutions for this problem. Gas turbines, reciprocating engines, and fuel cells rated highest in this category.

Gas turbines will fill the majority of these needs, with selected use of reciprocating engines, fuel cells, pumped hydro, CAES and possibly batteries. From a minimum revenue requirements basis gas turbines will be favored. Because of the high projected cost of SMES within this time frame it is unlikely that it will be able to compete in this market. Exhibit 5-6 compared the economics of SMES and the relevant competing technologies at various capacity factors. Capacity factors of .16-.33 correspond to 4000-8000 MWh for a 1000 MW SMES. SMES costs were developed for this comparison based on optimizing the storage capability to correspond to the capacity factor. If significant cost reductions are obtained there is the potential for SMES to become competitive by the year 2030.

5.5.2 Improve Load Following Ability

Over the next 10-15 years most of the needs in this area will be met by more traditional resources such as gas turbines and pumped hydro. Utilities do not specifically target resources for this application currently although there is a recognized need. It is anticipated that over the longer term there may be increased potential for technologies which provide load following support as utilities open up their transmission system to access and increased wheeling takes place.

The dynamic requirements of load following appear to be best met by batteries and SMES over the longer term for this application, and potentially flywheels. In Exhibit 5-4 batteries and SMES were ranked high for this application. The potential advantage here is the ability of these technologies to respond instantaneously to changes in load. Technologies such as gas turbines require non-instantaneous mechanical or electro-mechanical control system adjustments, such those in fuel flow, turbine valve position, or generator adjustments. SMES and batteries can adjust to changing load requirements instantly through electronic control adjustments of the Power Conditioning System (PCS). The current technical maturity of batteries will give them an advantage in the near term.

For dynamic applications such as load following, SMES could be sized such that the storage capacity could supply 10-15 minutes of energy at the rated output. Typical sizes for this would be 100-400 MW with 10-50 MWh of storage. This size application may be able to support multiple system needs and system benefits.

5.5.3 Reduce Energy Production Cost at Peak Demand Times

In comparing technologies which are attractive for reducing the cost of energy generation during peak demand periods, technologies which can be used for significant amounts of diurnal energy storage with high turnaround efficiency are most attractive. Pumped hydro, CAES and large SMES ranked highest on a technical basis in this application in Exhibit 5-4. Batteries, and flywheels do not appear to be attractive for longer duration storage times (>5 hours).

Pumped hydro and CAES will be the favored technologies for reducing peak power costs in the near term. Large SMES, which has several hours of energy storage capability has the technical capability to meet these needs, however, system cost will not be competitive in the near term. Large size increments of capacity and long construction times will also limit the attractiveness of SMES for this application. Over the longer term there is limited potential for SMES to become competitive if significant cost reductions are obtained (>70%).

5.5.4 Integrate Bulk Power Transfers

The ability to integrate NUG generation and inter-utility transfers of power is best performed by technologies which can respond instantaneously to pick up or reject load. Batteries, SMES and flywheels all appear attractive in this application. Storage technologies such as pumped hydro or CAES and generation technologies such as gas turbines and fuel cells are not typically used in applications requiring adjustments to power factor, or corrections to voltage sag problems.

The integration of power transfers from NUGs and power sales into the grid may also help to provide a long term market potential for SMES systems with 100-400 MW of power for 10-15 minutes. This type of device can help to solve several of the anticipated dynamic problems associated with coordinating generation. This is an area where traditional technologies have limitations; these problems can not be easily

solved by utility generation and traditional storage technologies may not provide adequate response and control. However, battery systems will present strong competition for SMES in this application.

Obtaining a greater understanding of these needs and development of techniques and methodologies for evaluating these problems will be required to justify these applications over the long run.

6.0 Transmission System Applications

6.1 Transmission Market Segment Definition

The utility industry has over 10,000 generating units totaling 700,000 MW in capacity with approximately 150,000 miles of high voltage transmission, and 1 million miles of distribution circuits. The total industry load is expected to increase 40-60% by the year 2030^[139], even though many utilities are showing excess capacity today. Although building a new transmission line to accommodate this growth is often today's preferred choice, utilities will find it increasingly difficult to site new transmission lines due to economic and environmental issues. As a result, there will be increasing pressures to operate transmission systems at higher transfer capacities.

The transmission market for new equipment can be defined to include:

- New and upgraded transmission lines and substations as a direct solution to the need for high capacity power delivery;
- Distributed generation that places the energy source near the load centers thus eliminating the need for transmission;
- And conventional and advanced compensation techniques to increase transfer capacity, enhance stability, and control flow.

SMES falls under the market segment of advanced compensation techniques that make use of high power semiconductors, operating under computer control, to dynamically supply or absorb both real and reactive power. Reactive power can either be dynamically supplied or absorbed by modulating fixed series or shunt capacitors and/or inductors, or by synthesizing a reactive current using forced commutated inverters. Energy storage devices, such as SMES or batteries, in conjunction with the inverter-type power conditioning system, are required for those applications that require the delivery or absorption of real power.

6.2 Transmission Problems and Needs

Within the transmission market segment, utilities are currently facing a variety of problems in the transmission of bulk power to the local distribution grids. Based on a review of utility system needs and interviews with transmission system designers and planners at 12 utilities, the major transmission related problems and needs can be grouped into the four categories of:

- Insufficient transfer capacity;
- Flow control, loop flows and bottlenecks;
- Voltage regulation, stability, and quality; and
- Transient and dynamic stability.

The four categories were evaluated to identify and rank the core problems or needs. These categories are directly interrelated in many cases. For example, the need to increase transfer capacity to accommodate load growth, could be inhibited by a system that is stability limited, or thermally limited, or experiencing voltage stability problems, or flow control problems.

The Transmission Problems Matrix shown in Exhibit 6-1 summarizes the interviews with 11 United States utilities and 1 Canadian utility. The utilities represented various geographic regions and varying transmission needs. Each of the four transmission problem categories were assessed for the year 2000 as being either a serious problem, of average concern, or of little concern. The significance of the utilities' responses were weighted, based on the utility's relative total generating capacity. A summation for each column (or problem) of the assessment multiplied times the weighting for each utility, results in the weighed total and corresponding ranking of problems. The problem and/or need are defined below in the order of importance:

6.2.1 Insufficient Transfer Capacity

Utilities anticipate a serious need to increase transmission transfer capacity to either meet the expected load growth, purchase lower cost power from remote locations (or purchase power as an alternative to the expensive retirement, demolition, and cleanup of outdated generating units), or wheel power for revenue opportunities. Environmental restrictions may prohibit utilities from building new transmission lines, or adding distributed generation in the vicinity of the load centers to meet these needs. Solutions to meet these needs must consider non-traditional technologically advanced alternatives.

Power flow in an ac transmission system is a function of the transmission line impedance, magnitude of the sending and receiving voltages, and the phase angle between these voltages^[11, 4.5-1]. Traditionally the transfer capacity can be increased by adding series capacitance, shunt compensation, or phase angle control. Dynamic control of real and reactive power using advanced compensation devices permit the system to have a transfer capacity approaching the thermal limitations.

6.2.2 Voltage Regulation/Voltage Stability/Power Quality

Many of the utilities have expressed a serious and growing concern relating to voltage regulation and voltage stability problems. These problems could result from excessive reactive voltage drops, developed in heavily loaded transmission lines, resulting in low voltage at the receiving end. In severe cases, during high demand periods the voltage stability margin could be reduced to a condition leading to voltage collapse where the utility traditionally sheds loads to recover.

Exhibit 6-1 Transmission Problems Matrix

TRANSMISSION PROBLEMS

WHATs vs. HOWs

Serious Problem/Need	●
Average Problem/Need	○
Minor Problem/Need	○

	WEIGHT	Insufficient Transfer Capacity	Flow Control/Loopflows/Bottlenecks	Voltage Regulation/Stability/Quality	Transient Stability/Dynamic Stability
Utility #1	3	●	○	○	○
Utility #2	2	●	○	○	○
Utility #3	3	●	○	○	○
Utility #4	1	○	○	○	○
Utility #5	1	○	○	○	○
Utility #6	2	○	○	○	○
Utility #7	1	○	○	○	○
Utility #8	3	●	○	○	○
Utility #9	3	○	○	○	○
Utility #10	1	○	○	○	○
Utility #11	2	○	○	○	○
Utility #12	1	○	○	○	○
Weighted Total		1 175	3 127	2 147	4 107
Rank		1	3	2	4

Some of the utilities interviewed expressed the need for proven analysis tools to model their system for voltage stability related problems. There is a concern that they cannot accurately assess the voltage stability margin, and voltage collapse could be much more likely than presently anticipated.

Included in this category are power quality problems resulting from momentary interruptions due to lightning strikes, and dirty insulators, as well as problems associated with excessive harmonic currents.

A less common problem identified was excessively high voltage at the receiving end resulting from the dominating effects of charging currents on lightly loaded transmission lines.

6.2.3 Flow Control/Loop Flow/Bottlenecks

Flow related problems generally fall into two categories:

- Loop flows where substantial quantities of power flow on neighboring utility transmission systems. Unwanted power flows could result in the infringing utility paying a fee to the neighboring utility for use of the transmission system. Unwanted power flows resulting from a contingency could also cause stability problems to the utility receiving the increased current flow.
- Bottlenecks in the transmission system may be limiting power transfer; series capacitance and inductance can be used to effectively control flow around potential bottlenecks.

The balancing of reactive power sources to control flow could have positive effects of lowering reactive current and reducing line losses; or could actually increase losses in cases where current flow is being throttled to bypass a bottleneck or prevent loopflow into a neighboring utility. Regional coordination is likely to discourage or prevent methods of flow control if it results in overall (multiple utility) system inefficiencies.

6.2.4 Transient Stability/Dynamic Stability

Stability related problems are categorized into transient stability and dynamic stability.

- Transient-stability refers to the amount of power that can be transmitted, with stability, following a major disturbance such as transmission system faults, sudden load changes, loss of generating units or line switching. Solutions to transient stability problems require dynamic control of high reactive and/or real currents for a few cycles.
- Dynamic stability involves the interaction of generating sources that undergo slow or gradual changes in operating conditions. Dynamic stability on power

systems is made possible by the action of automatic voltage regulators capable of increasing or decreasing flux within a synchronous machine thereby creating restoring forces equal to or greater than the disturbing forces^[174.2]. The stability limit of the system can be further increased by dynamically controlling reactive and/or real power compensation on the transmission system.

Stability, was ranked least important of the four transmission problem categories over the near term; however, it was recognized that as the transmission systems are "squeezed" to run at higher transfer capacities in the future, stability will become a major issue. Dynamic control of real and reactive power with FACTS and SMES technology has been analyzed as an effective means of expanding the transient and dynamic stability limits.

6.3 Evaluation Criteria

The evaluation criteria used in analyzing how well potential solutions satisfy utility problems/needs is divided into four major categories: technical performance, cost, environmental issues and risk. These major categories and associated sub-categories, as shown in Exhibit 6-2, were discussed with the utilities to establish a relative ranking based upon utility weighting and assessment of each criteria. The final weightings assigned to evaluate transmission solutions are:

• technical performance	50%
• economic characteristics	20%
• environmental issues	10%
• risks	20%

6.3.1 Technical Performance

This category measures the effectiveness of the candidate solution in meeting the technical performance requirements of a specific problem or need. The 12 utilities interviewed ranked technical performance as the highest valued selection criteria (this was tied with reliability and safety). Technical performance is considered a threshold criteria by utilities; meaning that a specific solution is eliminated from further evaluation if it does not meet a minimum performance specification. For this reason the combined weighted sum of the technical performance for the four transmission problems/needs is equal to 50% of the total evaluation criteria. The remaining 50% is divided among the subcategories under cost, environmental issues, and risk in relation to utility based ranking.

Exhibit 6-2 Transmission Evaluation Criteria

TRANSMISSION EVALUATION CRITERIA

WHATs vs. HOWs

Very Important	●●●
Important	●●
Not Important	○

	WEIGHT	TECHNICAL PERFORMANCE	LOW COST	Equipment Capital Costs	O&M/Efficiency	ENVIRONMENTAL ISSUES	Low EMF	Good Appearance/Small Size	RISK	Reliability & Safety	Technical Maturity	Vendor/Supplier Credibility	Ease of Regulatory Approval
Utility #1	3	●	●	●	●	●	○	○	●	●	○	○	○
Utility #2	2	●	●	●	○	●	○	○	●	●	○	○	○
Utility #3	3	●	●	●	●	●	○	○	●	●	○	○	○
Utility #4	1	●	●	○	○	●	○	○	●	●	○	○	○
Utility #5	1	●	●	●	●	●	○	○	●	●	○	○	○
Utility #6	2	●	●	●	○	●	○	○	●	●	○	○	○
Utility #7	1	●	●	●	○	●	○	○	●	●	○	○	○
Utility #8	3	●	●	●	○	●	○	○	●	●	○	○	○
Utility #9	3	●	●	●	○	●	○	○	●	●	○	○	○
Utility #10	1	●	●	●	○	●	○	○	●	●	○	○	○
Utility #11	2	●	●	●	○	●	○	○	●	●	○	○	○
Utility #12	1	●	●	●	○	●	○	○	●	●	○	○	○
Weighted Total		1 207		3 203	4 195	5 159	9 83		1 207	6 131	7 123	7 123	
Rank		1		3	4	5	9		1	6	7	7	

6.3.2 Cost

Utilities, in general, are required to select the most cost effective solution that meets their needs. The costs were divided up into two categories:

- Equipment/capital costs consists of the turn-key device or system cost including engineering design and installation costs; and
- Operating and maintenance costs. At the transmission level, O&M costs are principally costs of losses plus labor and equipment for line and substation maintenance and operation.

In most cases these two cost categories are lumped together in a least cost planning process. One exception was a utility that focused on the near term and considered up-front capital costs as the decisive criteria, even though long term an alternative solution may have a lower life cycle cost.

6.3.3 Environmental Issues

Two major transmission related environmental issues are EMF produced by the equipment, and the aesthetic appearance and size of the equipment. Both issues will strongly influence public acceptance of the solution, and the ease or difficulty in getting approval to install the proposed solution.

The impact regarding the potential health hazards due to transmission related EMF was of serious concern to all of the utilities interviewed (half assessed it as very important, the remaining half assessed it as important). The true impact of EMF is not understood, but the consensus is that field strength generated by the solution under evaluation will strongly influence the selection process.

Appearance and size of the solution under evaluation had mixed evaluations; southern and mid-western utilities having a lot of open area rated this as not important, however, east and west coast utilities ranked it as important.

6.3.4 Risk

The perceived risk will significantly influence the utility selection process. Risk, relating to transmission solutions, can be categorized as: reliability and safety, technical maturity, vendor/supplier credibility, and ease of regulatory approval.

- Reliability and safety were evaluated together under a single category. Reliability can be statistically predicted as mean time between failures (MTBF) and mean time to repair (MTTR) to give the utility a reasonable measure of the integrity of the system. However, experience with new technology may not as yet have statistical significance to accurately assess equipment failure rates. Safety relates to both operational and failure modes. This category, like technical performance,

was considered a threshold criteria; meaning that solution not meeting a minimum set of requirements will be eliminated from evaluation.

- Technical maturity is a measure of confidence, based on past experience, that the equipment will perform as designed for its expected life. Several of the utilities implied that their company would not purchase serial number 001; the solutions must be demonstrated as proven technology before utilities will buy-in.
- Vendor or supplier credibility addresses two questions: Will the equipment be produced by a single vendor (sole source) or multiple vendors? Are the vendors financially secure such that they will likely be around to support these solutions well into the future?
- The ease of obtaining regulatory approval will be influenced by above categories of need, cost, environmental issues, and risk. The approval process could very well drive a solution. For example, some utilities are expecting that it will be almost impossible to build new transmission lines in the future due to the environmental issues and therefore will look harder at alternative solutions such as FACTS and SMES.

6.4 Transmission Technology Comparisons

Several candidate solutions were measured against the evaluation criteria to best solve utility transmission needs. Exhibit 6-3 compares the top six solutions against the evaluation criteria. The analysis was performed using information obtained from vendor and utility interviews, and literature reviews and related Arthur D. Little experience.

The alternative solutions are listed below and ranked from best to least in meeting the combined transmission problems/needs of transfer capacity, flow control, voltage regulation and transient and dynamic stability.

6.4.1 New/Upgraded Transmission Lines

Constructing new transmission lines, and upgrading transmission lines to a higher voltage class, in many cases are the preferred choice to increase capacity and reduce line losses. Adding new transmission lines is becoming more difficult because of regulatory constraints and the lengthy approval process. Even though expensive, a utility is likely to elect to build new lines if the need exists and if permitted to do so; part of this reason is the fear that they will be unable to build new lines in the future.

Exhibit 6-3 Transmission Segment Analysis

TRANSMISSION SEGMENT ANALYSIS

WHATs vs. HOWs

Strong Characteristic	●
Average Characteristic	○
Weak Characteristic	○

	WEIGHT	New/Upgraded Transmission Lines	Conventional Compensation/Regulation	FACTS Compensation/Regulation	Advanced Flywheel Storage	Battery Storage	SMES
TECHNICAL PERFORMANCE							
Insufficient Transfer Capacity	20	●	○	○	○	○	○
Flow Control/Loopflows/Bottlenecks	10	●	○	○	○	○	○
Voltage Regulation/Stability/Quality	15	○	○	○	○	○	○
Transient Stability/Dynamic Stability	5	○	○	○	○	○	○
LOW COST							
Equipment/Capital Costs	10	○	○	○	○	○	○
O&M/Efficiency	10	○	○	○	○	○	○
ENVIRONMENTAL ISSUES							
Low EMF	7	○	○	○	○	○	○
Good Appearance/Small Size	3	○	○	○	○	○	○
LOW RISK							
Reliability & Safety	10	○	○	○	○	○	○
Technical Maturity	4	○	○	○	○	○	○
Vendor/Supplier Credibility	3	○	○	○	○	○	○
Ease of Regulatory Approval	3	○	○	○	○	○	○
Weighted Total		2 636	1 652	3 608	6 376	4 492	5 416
Rank		2	1	3	6	4	5

The reliability of transmission lines is outstanding when compared with alternative technologies. For example, a static VAR compensator will have about 20 hours of down time per year; equivalent new transmission line down time is two hours per year.^[172.12]

Utilities planners, engineering and operations personnel are comfortable working with new and upgraded transmission lines. The technology is well understood, and does not require sophisticated modeling of complex computerized control and communication systems.

6.4.2 Conventional Compensation/Regulation

Conventional compensation consists of: shunt capacitors, series capacitors, shunt inductors, series inductors, phase angle regulators, and voltage regulators (tap changers). These components can be fixed, or mechanically switched under manual or automated control. In some cases, automated high speed mechanical switching is used to stabilize the system following a contingency.

Conventional compensation is the by far the lowest cost means of increasing transfer capacity, controlling flow, and regulating line voltage. Utilities applying advanced transient analysis computer programs to characterize their systems are discovering that substantial improvements can be made with conventional compensation using automated high speed mechanical switching.

However, conventional VAR compensation does have limitations. For example:

- Control is limited to switching in discrete steps of fixed capacitance or inductance, and not as effective in solving stability problems as dynamic VAR compensation.
- The addition of fixed series capacitance to increase transfer capacity, a widely accepted practice in the Western region of the country, may introduce problems of subsynchronous resonance (SSR) at high levels of compensation.
- Fixed shunt capacitance loses some of its effectiveness in supplying VARs at lower voltages; this is particularly important during contingencies, and pre-voltage collapse conditions.

6.4.3 FACTS Compensation/Regulation

Flexible AC Transmission System (FACTS) (see glossary) devices are specifically designed to control power flow, increase transfer capacity, and improve system stability on transmission systems.

Early FACTS devices entering the market employ conventional thyristor control to modulate the current flow in inductors and capacitors used for high-speed vernier operation. These devices include:

- Static VAR compensator (SVC)
- Thyristor-controlled series compensator (TCSC)
- Thyristor-controlled phase regulator (TCPR)

FACTS technology, presently under development, employ gate turn-off (GTO) thyristors, in an inverter configuration, to generate synthesized voltage waveforms of controllable amplitude and phase; this technology can be used in conjunction with a capacitor, battery source, or SMES to deliver or absorb real and reactive power. Their is little or no difference between this FACTS technology and the SMES power conditioning system

The inverter-type FACTS devices include:

- Static condenser (STATCON)
- Unified power flow controller (UPFC)
- Advanced phase angle regulator (APAR)
- Advanced series compensator (ASC)

FACTS devices are specifically targeted to increase transfer capacity by solving voltage regulation, system stability, flow control and SSR problems. Exhibit 6-4 shows the relationship between the individual FACTS devices, their ability to supply/absorb real and reactive power, and the principle problems that they are intended to address.

Exhibit 6-4 Comparison of FACTS Modules for Transmission Applications

FUNCTION	TCSC ASC	TCPR APAR	SVC	STAT- CON	UPFC
Supply/Absorb Real Power				✓	✓
Supply/Absorb VARS	✓		✓	✓	✓
Voltage Regulation			✓	✓	✓
Power System Stability	✓	✓	✓	✓	✓
SSR Mitigation	✓				✓
Flow Control	✓	✓		✓	✓

Present research indicates that stability related problems can be more efficiently solved with the combination of real and reactive power under dynamic control. This implies that those FACTS devices (STATCON and UPFC) that can supply/absorb real power have a performance advantage, and perhaps an economic advantage, over

other FACTS devices for certain applications. (The STATCON is essentially SMES power conditioning electronics.)

6.4.4 Battery Storage

The analysis matrix in Exhibit 6-3 shows batteries and SMES as the two most attractive energy storage candidates for transmission applications. The problem areas best suited for these technologies are voltage regulation/stability/quality, and transient stability/dynamic stability. Transfer capacity will be increased as a result of improving the stability margins. The voltage regulation/stability problems are currently solved with reactive power (dynamic VAR control). The reactive power can be developed without energy storage and therefore is primarily a function of the power conditioning system. For applications requiring dynamic VAR control, a FACTS device (without energy storage) would be the cost effective solution.

Research has established that the combination of controlling both real and reactive power, is the most effective means mitigating transient stability and dynamic stability problems. The delivery of real power requires an energy storage system such as batteries, SMES, or electro-mechanical flywheel and their associated power conditioning electronics. The power conditioning electronics for the three technologies are very similar to the FACTS STATCON, and are not a major differentiating factor in the selection process.

Battery storage was ranked highest among the three technologies because of the low capital cost of lead acid batteries, and lower risk associated with this mature technology. However, transmission transient stability applications requires a high rate of charge and discharge for a brief period of time (high power/energy ratio, MW/MW-sec). A typical size power and energy storage requirement for transmission applications is 500 MW/500 MW-sec (139 kWh). Lead acid batteries cannot be repeatedly deep discharged, or rapidly charged, without severely shortening the battery life. For transient and dynamic stability applications the batteries should be oversized by approximately 50 to 100 times the required energy storage in order to have a 5 to 10 year life (less than 2% of the total energy capacity for each discharge or charge cycle). Therefore, a transient stability application would typically require 13.9 MWh of battery energy storage in the year 2000. Advanced battery development should reduce the oversize requirement in high P/E applications to effectively lower the capital, and replacement, cost for the energy storage component by the year 2030.

Exhibit 6-5 lists representative battery storage system costs for transmission applications, along with the relative percentage of PCS costs versus storage costs.

Exhibit 6-5 Storage Technology Cost Comparison For 500 MW/500 MW-sec Transmission Application

TECHNOLOGY	YEAR 2000		YEAR 2030	
	Battery ⁽¹⁾	SMES	Battery ⁽¹⁾	SMES
Total System Cost (Million \$)	35.5	60.0	18.5	30.0
PCS Cost % of Total	92%	60%	88%	60%
Storage Cost % of Total	8%	40%	12%	40%
Operating & Maintenance Costs (Million \$/Year)	3.0	1.2	3.0	0.8

(1) Battery cost based on being 100 times oversized to provide long life (i.e., 50,000 MW-sec).

6.4.5 SMES

The need to improve transmission stability is the best opportunity for SMES in utility applications. SMES units requiring a much lower power to energy ratio are not cost effective when compared to alternative technologies such as battery storage and FACTS. The typical size of a SMES unit for transmission applications would be 500 MW/500 MW-sec. The cost of the SMES energy component, although relatively high when compared to battery storage, is still dominated by the power condition costs for this size unit.

The highest weighted evaluation criteria in Exhibit 6-3 for transmission applications are: technical performance, capital cost, and O&M/efficiency (including battery replacement cost). SMES technology is ranked highest under technical performance for transient/dynamic stability applications. It is unmatched in its ability to deliver or absorb large amounts of energy in a very short period of time. SMES has the advantage over FACTS technology (excluding FACTS with energy storage) in that it can supply/absorb both real and reactive power. A serious need will exist in the year 2030 when transient and dynamic stability problems will be more common. Future stability problems will require very high technical performance that could justify the expense of SMES.

Exhibit 6-5 compares the capital and operating and maintenance costs of SMES and battery technologies. The power conditioning system for the two devices are of comparable costs and are not a differentiating factor in the evaluation. Batteries clearly have the cost advantage over the near term. In the year 2030, the capital costs are projected to be closer, and SMES operating costs significantly lower. SMES should compete evenly with battery technology in the year 2030, and is likely to gain market share in years following 2030.

6.4.6 Advanced Flywheel Storage

Electromechanical flywheels were evaluated as candidate solutions for the energy storage component for transmission applications. Advanced flywheel design is based on operating a lightweight, glass, polymer, or graphite fiber rotor/flywheel on magnetic bearings, in a vacuum containment, at very high speeds.

Advanced flywheels have been under development for approximately 20 years and have not yet matured. This technology was ranked least favorable of the six solutions for transmission applications primarily due to high capital cost and high risk associated in the development and operation of a 500 MW/500 MW-sec sized unit. Although smaller units are viable solutions for customer service problems/needs (reference Section 8.4), the larger high power units required for transmission applications do appear practical. These high power units require bigger, heavier motor/generator rotors thus losing their lightweight high speed advantage.

6.5 Transmission Market Segment Conclusions

The high priority problems faced by utilities in the transmission area of the electric utility industry include:

- Insufficient transfer capacity,
- Voltage regulation/stability/quality,
- Flow control/loop flow/bottlenecks, and
- Stability (transient/dynamic).

The best transmission market opportunities for SMES will be in meeting needs that require the dynamic control of real and/or reactive power; this would primarily relate to improving dynamic and transient stability of transmission lines. By improving the stability of the transmission system, utilities will be able to transfer more energy by operating the system near its thermal limits.

Improving the stability of transmission systems is not recognized as a primary need today, but will become more and more significant as approval to site new transmission lines becomes more difficult and more demands are placed on increasing transmission capacity of existing lines. The need for dynamic stability control will begin to be important to utilities by the year 2000, and very important by the year 2030.

Some stability problems can be controlled with conventional technology with high speed switching of series and shunt compensation. More effective control can be accomplished using FACTS technology to actively control reactive power and/or phase angle. An energy storage device combined with the FACTS-type power conditioning has the added benefit of being able to absorb and deliver real power. The competing energy storage system for this application is batteries. Batteries have a low capital cost, but must be oversized for high P/E applications. The advantages of SMES over batteries includes very high energy charge/discharge, low maintenance, long life, and low environmental impact.

Preliminary studies indicate^[171.5] that the ability to deliver and absorb both real and reactive power is most effective for stability control. A device that delivers/absorbs real and reactive power could require a smaller sized power conditioning system than a device that only delivers/absorbs reactive power. This suggests that there may be an economically optimum ratio of power capacity to energy storage for energy storage devices designed for stability control.

The estimated size of a typical energy storage device for transmission stability control is 400-600 MW of power capacity and 400-600 MW-sec of energy storage. The need for a high power capacity to energy storage ratio (P/E) is well matched by the benefits of SMES without excessively high energy storage costs. The energy storage costs of a SMES device this size is approximately 40% of the total device cost; the remainder of the cost is in power conditioning.

7.0 Distribution Applications

7.1 Distribution System Market Segment Definition

Often transmission and distribution are lumped together as a single part of the electric power system. Sometimes they are assigned a combined function under the term "power delivery", since that is clearly one role they have in common, as distinguished from generation.

However, in a market assessment for new technologies it is important to maintain a distinction between transmission and distribution. The transmission system generally represents about 10% of total utility system investment and is characterized by a relatively small number of high cost pieces of equipment. The distribution system is often 25 to 40% of total investment and is characterized by a large volume of relatively low cost items of equipment. For the most part, electrical equipment manufacturers view these as separate markets.

Furthermore, the power delivery terminology is an over-simplification. In the transmission system it is not unusual to find the justification for new facilities to be based more on the enhancements that transmission brings in the improved utilization and integration of generation facilities than on the load-carrying role. Power delivery tends to be an oversimplification of the role of the distribution subsystem, as well. For example, generation resources can be located within the distribution system and at end-user sites. Demand-side management (DSM) and distribution automation bring a significant element of control which may override traditional power delivery functions.

In the context of U.S. power systems the distribution system usually means utility-owned equipment at the lowest two voltage levels up to the customer meter at the service entrance. The system is comprised of distribution substations, primary distribution circuits, distribution transformers, and secondary distribution circuits which supply the majority of end-users of electrical energy. Some larger commercial and industrial end-users may be supplied directly from primary distribution circuits, or even from the transmission system, but most customers are served by the secondary system at voltages ranging from 120/240 volt single-phase to 208 and 480 volt three-phase. Primary distribution voltages generally range from 2400 volts to 34,500 volts (34.5 kV).

Distribution substations are supplied by the transmission (or subtransmission) system, which is usually networked. Primary and secondary distribution systems supply end-users in a radial system, for the most part. However, in higher load density urban areas distribution supply is frequently networked also.

7.2 Distribution System Problems and Needs

The problems which arise at the distribution level in the power system in the foreseeable future will vary widely in character and frequency of occurrence depending upon both system and load characteristics. A ranking and weighting of problems based on telephone interviews with distribution engineers in eight utilities is shown in Exhibit 7-1. While this is a limited sample, it includes some of the largest utilities in the U.S. and gives an indication of the significance of problems anticipated at the distribution level. The three top-ranked problems are:

- Local-Generation-Related Problems
- Long Duration Power Quality and Reliability Problems
- Capacity Limitation Problems - Equipment Overloads/Excessive Fault Levels

7.2.1 Capacity Limitations

Capacity limitation problems may be characterized as follows:

- Equipment overloads
- Excessive voltage drop
- Poor power factor
- Excessive losses
- Fault levels in excess of breaker interrupting duties

For the most part, these are all traditional problems occasioned by load growth on existing systems. However, in the context of a long range market assessment these problems may be accentuated with the advent of new loads, e.g., electric vehicle battery charging. Such loads may significantly change the time of day of system peak loads, the duration of peak loads, and the diversity characteristics of loads.

In some cases local area load growth may not be the cause of capacity limitations. Such problems may occur even on portions of the distribution system which are relatively static, i.e. where load growth is negligible. Equipment on circuits in such areas may be exposed to ever-increasing levels of fault current because of reduced source impedances on the high-voltage side of the distribution substation. In other words, equipment on the distribution system in a low- or no-growth area may be overstressed in time by a strengthening of the generation-transmission system occasioned by growth elsewhere.

DISTRIBUTION PROBLEMS

WHAT'S vs. HOWs									
Utility #1	2	3	1	2	2	3	2	3	2
Utility #2	3	1	2	2	3	2	3	2	3
Utility #3	1	2	2	3	2	3	2	3	2
Utility #4	2	2	3	2	3	2	3	2	3
Utility #5	2	3	2	3	2	3	2	3	2
Utility #6	1	2	2	3	2	3	2	3	2
Utility #7	2	3	2	3	2	3	2	3	2
Utility #8	1	2	2	3	2	3	2	3	2
Weighted Total	84	80	92	84	80	92	84	80	92
Rank	2	4	1	2	4	1	2	4	1
WEIGHT									
Capacity Limitations									
Equipment Overloads/Load-Growth-Related Problems									
Excessive Fault Levels/G&T-System Growth-Related Problems									
Local-Generation-Related Problems									
Power Reliability & Quality									
Short Duration Variations & Interruptions									
Impulse & Oscillatory Disturbances									
Waveform Distortion & Harmonics									
Long Duration Variations as Interruptions									

☒ Serious Problem/Need
☒ Average Problem/Need
☐ Minor Problem/Need
☐ -none

7.2.2 Problems Related to Generation Additions at the Distribution and Customer Service Levels

As electric power systems have grown over the past century a major trend has been that of ever-increasing generation unit size and higher voltage transmission. The forces driving this trend have been generation economics of scale and the significant improvements in power transfer capability and efficiency associated with EHV transmission.

In recent times economies of scale have diminished and new transmission is difficult to implement. To meet customer needs competing trends have developed, including Demand-Side Management (DSM) and increased use of small generation at distribution and end-use levels. In theory the concept of localized generation close to the load has merit. It reduces system losses and avoids transmission investment. In practice, it introduces potential problems of increased power costs, system protection, stability, public and employee safety, reliability and power quality, and, in some cases, environmental impact. Local generation close to the load is a legitimate alternative to be evaluated, but it brings its own problems which need to be addressed.

Local generation is referenced by several names:

- Distributed Generation
- Modular Power Systems
- Dispersed Storage and Generation (DSG)

Examples of technologies which are usually included are:

• Small Scale Reciprocating Engines	• Flywheels
• Small Scale Gas Turbines, incl. Cogeneration	• Batteries
• Photovoltaics	• SMES
• Wind Generators	• Wind Generators
• Fuel Cells	• Small Hydro

Some of these are more technologically mature than others and are well-established, especially in end-use applications. Some may be well-suited in specific conditions for joint use, where the combined benefits of rapid response (flywheels, SMES, batteries) may complement the longer duration, slow-start capability of a diesel generator or a gas turbine.

Many of the problems of local generation arise because the existing local system has been designed for a single supply point at the distribution substation. In the U.S. most distribution is radial and normal power flow and fault current flow is uni-directional. Even in the case of networked distribution in high load density urban areas, the low-voltage network is designed to receive supply from the bulk power system at distribution substations.

The addition of local generation to systems not designed for it introduces problems under both normal and emergency operating conditions. The study of the technical and economic feasibility of local generation must include proper consideration of measures to maintain safety, reliability, quality, and economy of electric service.

7.2.3 Power Reliability/Quality Problems

Power reliability problems are characterized as follows:

- Excessive frequency and/or duration of customer interruptions
- Transients
 - impulse
 - oscillatory
- Long duration variations
 - overvoltages
 - undervoltages
- Short duration variations
 - voltage sags and swells
 - momentary/temporary
- Harmonic distortion
 - voltage
 - current
- Flicker
- Outages

The first category, customer interruptions, is a system reliability problem area. At the distribution level it is always a major concern in system operation and design, since studies have shown that over 80% of all customer interruptions are the result of equipment outages on distribution circuits, usually due to lightning, ice storms, tree branches, etc.

The remaining categories are subsets of the power quality problem. While improvements in reliability of service are usually addressed only on the utility side of the meter, power quality is somewhat more complex, since it is not just a utility problem. Voltage disturbances and harmonics at times have their origins in the performance of the utility-owned system and equipment, but they also often arise from the many types of sensitive end-use equipment bins placed into service today. Not only are computers and devices employing solid-state power converters particularly vulnerable to momentary disturbances in the power supply, but such equipment and other loads like adjustable speed motor drives, solid-state controls, and various non-linear loads can be sources of disturbances and harmonics. Thus, customer loads can affect the performance of other customer loads.

Power quality is properly addressed, not as a utility problem, but as an electrical system problem involving both supply and demand-side considerations.

7.3 Evaluation Criteria

In order to define how well potential solutions will satisfy utility distribution problems, we developed a list of prioritized criteria used in utility decision making. A preliminary list of criteria was refined using a series of utility interviews to a) prioritize the criteria (high/medium/low) b) add additional criteria, and c) delete unnecessary criteria. The criteria have been grouped into four major categories: technical performance, economic, environmental issues, and risk. The Distribution Criteria Matrix (Exhibit 7-2), is a summary of the survey results regarding the importance of the evaluation criteria. The final weightings used in evaluating distribution solutions are:

- technical performance - 30%
- economic characteristics - 40%
- environmental issues - 10%
- risk - 20%

Cost and technical performance are the principal measures of merit for alternative solutions at this level. The various types of risk are roughly equally clustered as a third group, and environmental issues are ranked last. EMF is generally of greater concern than appearance.

7.3.1 Typical Performance Criteria

Typical technical criteria which a proposed problem solution must meet at the distribution level are:

- Voltage limits - voltage on the distribution system at customer meters must usually be constrained within a fairly narrow range. The precise range may vary from one regulatory jurisdiction to another and may be stated as a voltage range such as 114 to 126 volts, or as a nominal 120 volts, plus or minus 5%. While these limitations apply at the secondary, or customer supply voltage, level they often affect solutions to be implemented on the primary distribution system, or at the distribution substation.
- Thermal limits - transformers, overhead conductors, and underground cables all have overload limits, usually expressed as a percentage of some nominal, or rated, amperes or kVA, and also often specified with time duration and ambient temperature limitations.
- Response time requirements - in the resolution of some power quality problems and, for example, problems with the dynamic response of motors to system disturbances a key attribute of a solution may be rapid response.

Exhibit 7-2 Distribution Evaluation Criteria

DISTRIBUTION EVALUATION CRITERIA

WHATs vs. HOWs

Very Important	●●●
Important	●●
Not Important	●
	1 2 3

	WEIGHT	TECHNICAL PERFORMANCE	LOW COST	Equipment Capital Costs	O&M/Efficiency	ENVIRONMENTAL ISSUES	Low EMF	Good Appearance/Small Size	RISK	Reliability & Safety	Technical Maturity	Vendor/Supplier Credibility	Ease of Regulatory Approval
Utility #1	2	●	●	●	●	●	○	○	●	○	○	○	○
Utility #2	3	○	●	●	●	●	○	○	●	○	○	○	○
Utility #3	1	●	●	●	●	●	○	○	●	○	○	○	○
Utility #4	2	○	●	○	○	●	○	○	●	○	○	○	○
Utility #5	2	●	●	●	●	●	○	○	●	○	○	○	○
Utility #6	3	●	●	●	●	●	○	○	●	○	○	○	○
Utility #7	2	○	●	●	●	●	○	○	●	○	○	○	○
Utility #8	1	●	●	●	●	●	○	○	●	○	○	○	○
Weighted Total		3 116		1 136	1 136		8 48	9 40		4 80	5 76	6 64	7 60
Rank		3		1	1		8	9		4	5	6	7

- System fault and protection limitations - some alternatives at the distribution level, such as local generation, etc., impose excessive fault duty on existing protection equipment, in addition to affecting protective device coordination and raising safety concerns. Such effects and their resolution must be considered in an evaluation of alternatives.
- Other technical criteria may include guidelines on acceptable equipment outage rates, customer interruptions, levels of harmonics, etc.

7.3.2 Economic Criteria

In planning, engineering, and operating a power system the economic comparison of alternative solutions to problems is commonly based on a determination of the revenue requirements associated with each alternative. Revenue requirements are based on the levelized fixed and variable costs of the alternative over the life cycle of the asset.

Fixed costs are charges related to the capital investment required to implement the alternative and replace it at the end of its expected useful life. Capital investment includes, for example, design and engineering, purchase price of materials and equipment, construction and installation costs including interest on funds used during construction, test, and start-up. Fixed costs also include return on investment (weighted average cost of debt and equity), depreciation, income taxes, insurance, and property taxes.

Variable costs are charges related to any year-to-year variations in the operating cost of an alternative. At the generation level variable costs are usually dominated by fuel costs. At the transmission and distribution levels variable costs are mostly losses and O&M costs.

7.3.3 Environmental Criteria

At the distribution level as at transmission, EMF and appearance are issues which may influence public acceptance and the choice of a solution. For distribution solutions involving local generation and some storage technologies, air, noise, and water quality may also be important factors.

7.4 Distribution Technology Comparison

At the distribution level, solutions to the problems described in Section 7.2 may be classified as follows:

7.4.1 New/Upgraded Distribution Systems and Equipment

Capacity limitation problems are commonly addressed in this way. The nature of this solution depends on the seriousness of the problem. Some utilities experiencing load growth on a predominately 4 kV distribution system may face widespread chronic

problems of equipment overloads, transformer failures, excessive voltage drop, etc. The long term solution in these cases may call for comprehensive system redesign and voltage upgrade to a 15 kV class system or higher. In other cases of less widespread problems, solutions may be less pervasive and involve only transformer rating upgrades, line reconductoring, etc.

7.4.2 Conventional Compensation/Regulation

Solutions in this category include fixed and switched shunt capacitors, line voltage regulators, and load tap changing (LTC) on substation transformers. Such measures are often used to address specific local problems of excessive voltage drop, poor power factor, equipment overloads, excessive losses, etc.

7.4.3 FACTS Compensation/Regulation

While most applications of FACTS-type devices are under study at the transmission level, there is an increased attention at the distribution level, as well. The static condenser (or STATCON) and the static VAR compensator (or SVC) are two devices which can be applied at the distribution level. The STATCON is a solid-state controller, functionally equivalent to a synchronous condenser, which can supply capacitive, as well as inductive, reactive power. The SVC addresses the problem of voltage control by using thyristors to rapidly add or remove shunt-connected reactors and/or capacitors. The SVC has been used since the 1970's, while STATCON technology is currently being developed by EPRI. While these may not be a cost-effective alternative for most distribution system reactive problems, it may be an improved approach for some power quality problems and for resolving dynamic problems experienced on some circuits with heavy motor loads (see Section 7.4.6, below).

7.4.4 Protection System Upgrade

Growth of customers and loads on existing circuits, decreased system source impedances (stronger system ties), and local generation are all reasons for protection system inadequacies. These may result in increased frequency and duration of customer interruptions. Upgrades in the ratings, types, and locations of protective devices are often the principal solution to such problems.

7.4.5 DSM Automation

The orientation and justification of demand-side management (DSM) is usually the achievement of generation deferral benefits. To the extent distribution system peak loads are concurrent with peaks at the bulk power supply system level there may be benefit in relief of distribution capacity limitation problems, as well. However, DSM may in some cases create new capacity limitation problems on distribution systems (the "payback" phenomenon), so DSM measures must be carefully examined as distribution-level solutions.

Distribution automation has possibilities for significant contributions to both capacity limitation problems and reliability problems.

7.4.6 Premium Service

The provisions of premium service by a utility to an industrial or commercial customer experiencing power quality or reliability problems is clearly one solution at the distribution level. In exchange for a higher rate structure the utility provides an alternate source of supply, perhaps a redundant circuit from a nearby substation, or an emergency generator.

An advanced premium service concept, typically referred to as "Custom Power," is the focus of an EPRI-sponsored technology program. This program is currently developing distribution STATCON technology (as discussed in Section 7.4.3, FACTS Compensation/Regulation) and solid-state circuit breakers to improve the quality of power to either a large customer or a group of smaller customers clustered within an industrial/commercial park. This advanced concept addresses a potential customer preference to pay a higher electric rate for custom power rather than install equipment to condition power for their specific needs. When equipped with a properly sized energy storage device, the STATCON has the capability to supply real power to the load for voltage sags or momentary interruptions caused by system faults or motor loads. Preliminary energy storage requirements for the "Custom Power" concept (which requires dual feeders) are approximately 100 to 300 kW (assuming 3 cycles of storage at 2 to 5 MVA) and will be addressed in the near term using conventional capacitor technology.

For future power quality applications at the distribution level in which dual feeders are not feasible, an energy storage device integrated with STATCON technology may be needed to address the power quality problem associated with voltage sags and momentary interruptions.

7.4.7 Distributed Generation

Smaller generation units located at appropriate points on the distribution system and at customer locations may be an alternate solution to some distribution problems. For the purposes of this assessment, three distributed storage technologies - flywheels, batteries, and SMES, are included among the solutions to be considered (see Section 8 for a discussion of each technology).

Energy storage technologies have the potential to bring benefit to all segments of the power system. Generally, as one moves through the power system from generation to end-user the loading of equipment is such that daily load factors are reduced. Thus, a residential customer might have a daily load shape with a 10% or 15% load factor, whereas at the generation level it may grow to 60% or higher. This means that conditions for the beneficial application of storage tend to improve at lower levels of the system.

To the extent that simultaneity of benefits may exist, e.g. resulting from a coincidence of daily peaks at generation and distribution, benefits across the system may be additive, and incentive for placing storage close to loads, at either distribution or selected end-users, increases.

As noted in Section 7.2 generation located on distribution circuits and at end-users is often classed as a problem, rather than a solution to problems. This is particularly true of rotating equipment (MG sets, gas turbines, small hydro, wind machines, etc.) which may contribute to increased fault levels, out-of-phase switching, and stability problems. Storage devices such as advanced flywheels, batteries, and SMES are normally linked to the system via a power conversion system (PCS). While such devices do not necessarily contribute significantly to fault levels they may make it difficult to extinguish arcs if they continue to operate during system protective equipment operations.

In spite of such problems increased distributed generation is likely to continue as a trend because in specific utility situations it brings sufficient system-wide benefit, or because in specific end-user cases it improves the performance of an industrial process, for example. Careful attention to integrating the operation and control of distributed generation with the control of the distribution system during both normal and emergency conditions is expected to resolve problems.

7.5 Analysis of Distribution Alternatives

The dominant problems at the distribution level are:

- Problems related to distributed generation,
- Power quality and reliability, and
- Capacity limitation problems.

An overall ranking of solutions at the distribution level to problems at this level is given in Exhibit 7-3. In the context of the dominant criteria (cost and technical performance) which are based on the Section 7.3 evaluation, and the significant problems from Section 7.2, the solutions which rank highest represent fairly traditional measures:

1. Conventional Compensation/Regulation
2. Protection System Upgrade
3. New/Upgraded Distribution Equipment
4. DSM and Automation

Except for premium service, which usually involves conventional technology but can be costly to implement, the remaining solutions represent relatively new approaches or technologies, including the three storage technologies considered.

Exhibit 7-3 Distribution System Analysis Matrix

DISTRIBUTION SYSTEM ANALYSIS
Evaluation Criteria vs. Alternative Solutions

WHATs vs. HOWs

Strong Characteristic	●
Average Characteristic	○
Weak Characteristic	○

	WEIGHT	New/Upgraded Distribution Equipment	Conventional Compensation/Regulation	FACTS Compensation/Regulation	Protection System Upgrade	DSM & Automation	Premium Service	Advanced Flywheel Storage	Battery Storage	SMES
TECHNICAL PERFORMANCE										
Capacity Limitations	10	●	●	●	●	●	○	○	○	○
Local-Generation-Related Problems	10	○	○	○	○	○	○	○	○	○
Power Reliability & Quality	10	○	○	○	○	○	○	○	○	○
LOW COST										
Equipment/Capital Costs	20	●	●	○	○	○	○	○	○	○
O&M/Efficiency	20	●	●	○	○	○	○	○	○	○
ENVIRONMENTAL ISSUES										
Low EMF	3	○	○	○	○	○	○	○	○	○
Good Appearance/Small Size	7	○	○	○	○	○	○	○	○	○
LOW RISK										
Reliability & Safety	10	●	●	○	○	○	○	○	○	○
Technical Maturity	3	●	●	○	○	○	○	○	○	○
Vendor/Supplier Credibility	3	●	●	○	○	○	○	○	○	○
Ease of Regulatory Approval	4	●	●	○	○	○	○	○	○	○
Weighted Total		3 672	1 780	5 352	2 752	4 556	8 292	7 312	6 336	9 288
Rank		3	1	5	2	4	8	7	6	9

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7.5.1 Distributed Generation

Due to the diminishing economies of scale associated with large generation units and the difficulties in siting new transmission facilities, the competing trend towards local generation at the distribution and end-use level is becoming more accepted.

However, distributed generation also creates a set of problems (e.g. decreased system protection and stability, increased fault levels) which are best solved by protection and distribution system upgrades. Energy storage solutions are not applicable for this distribution problem.

7.5.2 Power Quality

Two significant distribution problems are associated with power quality and reliability: long duration variations and interruptions resulting from equipment outages and short duration variations and interruptions due to temporary system faults and large end-user loads. Energy storage technology is not practical for solving the long duration problem. However, for selected commercial and industrial applications, a storage device may be a practical solution for high-use customers with critical processes that rely on sensitive microprocessor-based equipment. As shown in Exhibit 7-4, two storage size ranges are appropriate for distribution-level applications which solve the voltage sag or momentary interruption problem lasting 2 seconds (or less). The three technologies considered for these applications include batteries, flywheels, and SMES technology. In general, the high energy storage and operating costs of SMES technology relative to batteries and flywheels will create a poor competitive position for SMES in voltage sag applications at the distribution level. (See Section 8, Customer Service Applications, for a discussion of the costs associated with each technology). Furthermore, the market opportunity for an energy storage device at the distribution level is limited because the majority of distribution feeders serve a broad mix of customer types; many of these customers do not have a strong need to solve the short duration power quality problem.

Exhibit 7-4 Typical U.S. Distribution Circuit

Customer Type	No. of Customers	Cumulative MVA Load
Residential	900	2.0
Commercial	90	1.7
Industrial	9	2.1
Street Lights, Municipal, etc.	1	0.2
Totals	1000	6.0

This may be illustrated by considering a typical U.S. distribution circuit. Using national statistics, such a circuit might supply a total load of 6 MVA and approximately 1000 customers having the breakdown as shown in Exhibit 7-4.

A storage device designed to solve a two-second power quality problem for this entire circuit would be sized at 6 MW and 12 MW-sec. The cost of such a device would have to be reflected in the rates for all customers, whether or not they need or want to pay for such a level of service quality.

A two-second service interruption may be of major significance to an industrial customer since it may result in a costly production process interruption. A more equitable application of a storage device would seem to be to size and locate it to benefit the industrial customer. The cost would then be reflected in the rates charged to this industrial customer.

In terms of a market assessment for storage devices at the distribution level to solve power quality problems, this would focus on specific applications in the supply lines to larger end-users. This may include both commercial and industrial customers on either the utility or customer side of the meter in which this becomes a customer service application that will be addressed in Section 8.

7.5.3 Capacity Limitations

Capacity limitations at the distribution level create a variety of problems including equipment overloads, excessive voltage drop and losses, poor power factor, and increasing fault levels. These problems are typically solved by applying one or more of the four solutions previously described: new/upgraded distribution equipment, demand-side load management, distribution automation, and protection system upgrades.

In general, energy storage technologies are not highly ranked solutions for the capacity limitation problem category. This is primarily driven by economics. A transformer overload problem, for example, could be solved by a storage device located on the load-side of the transformer. The storage device would provide additional benefits of load leveling. However, this may not be justified on an economic basis. The installed cost of a new transformer is of the order of \$15-25/kVA, whereas the cost of storage capacity appears to be at least on order of magnitude higher.

Specific applications of energy storage, however, are more feasible when benefits are simultaneously realized at the transmission and generation level. As shown in Exhibit 7-5, three storage sizes are applicable for solving capacity limitation problems at the distribution level. Similar to the conclusions for power quality applications, SMES, flywheels, and batteries are all applicable technologies which can meet the technical requirements, however, the high energy storage and operating costs of SMES technology becomes a significant disadvantage relative to the competing solutions and will severely limit the market opportunity for SMES in distribution load-leveling applications.

In looking at the market potential for storage devices for application at the distribution level for capacity limitation problems, it becomes apparent that a coincidence of benefits with the needs at higher levels of the utility system will be required to make storage devices attractive.

Exhibit 7-5 Distribution-Level Energy Storage Device Size Ranges

Storage Device Location/Application	Ranges of		
	MW	MW-sec	MWh
Distribution substation low voltage bus			
For short duration power quality & reliability	6 - 40	12 - 80	—
For capacity limitations	1 - 10	—	2 - 20
Head of a general distribution feeder			
For short duration power quality and reliability	3 - 10	6 - 20	—
For capacity limitations	0.5 - 2	—	1 - 4
Feeder supplying an industrial park or large end-user			
For short duration power quality & reliability	3 - 10	6 - 20	—
For capacity limitations	0.5 - 2	—	3 - 12

8.0 Customer Service Applications

8.1 Customer Service Market Segment Definition

The awareness of "power quality" and energy conservation by industrial, commercial, and residential customers has significantly increased during the past several years. Many customers with critical manufacturing processes and computer-based services are beginning to understand the relationship between the quality of electrical power and the performance and reliability of electronic equipment. In addition, utilities are now offering new rate structures, demand-side management programs, and direct control of end-use loads which have made customers aware of the economic incentives associated with energy conservation and load deferral.

The customer service market can be defined as all power conditioning and demand-side management equipment installed on the customer side of the electric meter. The power conditioning market is extremely broad in terms of the types of equipment available today. However, the specific market segment which relates to micro-SMES and other energy storage technologies is primarily focussed on eliminating the voltage "ride-through" problems associated with the sensitive equipment within large commercial and industrial manufacturing facilities. Ride-through requirements for this narrowly defined market segment would be a minimum of 2 seconds with a 1 to 5 MVA capacity.

8.2 Customer Service Problems and Needs

During the next decade, the majority of customer service problems and needs fall under two general categories: power quality and improved energy utilization. The matrix shown in Exhibit 8-1, provides a ranking of the problems experienced today by commercial and industrial customers. The data needed to assess the importance of each problem was derived from interviews with utility personnel, power quality experts, and technical facility managers of large commercial and industrial plants or buildings. The lower the ranking number shown in Exhibit 8-1, the more important the problem is for the end-user. Each problem or need, their associated causes or drivers, and their importance to the customer are discussed in subsequent sections.

8.2.1 Power Quality

Power quality problems can be defined, in general, as any deviation from a constant voltage, 60 Hertz (Hz) sine wave. Several definitions and terms now exist for categorizing specific power quality problems. Although the quality of the power delivered by the utilities has not significantly changed in the past 10 to 20 years, the sales of power conditioning equipment to protect against power quality problems is increasing by more than 20 percent per year.^[138,145,146]

Exhibit 8-1 Customer Service Problem Matrix

CUSTOMER SERVICE PROBLEMS

WHATs vs. HOWs

Serious Problem/Need	●	5
Average Problem/Need	○	3
Minor Problem/Need	○	1

		WEIGHT									
			1	2	3	4	5	6	7	8	9
Interview #1	1	1	●	○	○	○	○	○	○	○	○
Interview #2	2	1	○	○	○	○	○	○	○	○	○
Interview #3	3	1	○	○	○	○	○	○	○	○	○
Interview #4	4	1	○	○	○	○	○	○	○	○	○
Interview #5	5	1	○	○	○	○	○	○	○	○	○
Interview #6	6	1	○	○	○	○	○	○	○	○	○
Interview #7	7	1	○	○	○	○	○	○	○	○	○
Interview #8	8	1	○	○	○	○	○	○	○	○	○
Interview #9	9	1	○	○	○	○	○	○	○	○	○
Interview #10	10	1	○	○	○	○	○	○	○	○	○
Weighted Total	1			38	38	30	26	42	30	14	1
Rank	2			3	3	5	1	2	5	7	2

The increase in the number of power quality related problems can be attributed to:

- A substantial increase in the number of electronic loads;
- Higher sensitivity of modern electronic loads to disturbances created both locally within the customer facility, and externally, by transmission and distribution system faults, capacitor switching, or other conditions;
- An increase in the application of interconnected electronic hardware (e.g. computer local area networks); and
- The manner in which loads draw their energy from the power source (e.g. capacitor charging near the peaks in switch-mode power supplies).

In order to assess the importance of power quality, four major problem categories were described during our interviews: (1) short duration rms variations and interruptions, (2) impulsive and oscillatory disturbances, (3) waveform distortion, and (4) long duration rms variations and interruptions. Based on our interview data and the efforts of two recently established IEEE power quality working groups, a discussion of the relative importance of each problem and a problem definition is provided in the following sections.^[165,166]

Short Duration RMS Variations & Interruptions. Our interview data indicates that short duration rms voltage variations and interruptions are the most important problem identified by large commercial and industrial customers. Within the context of our interviews, the broad disturbance category of "short duration variations and interruptions" was conveyed as voltage sags and interruptions with less than a 2 second duration. A voltage "sag" is typically defined as a voltage reduction to a level less than 85 per cent of the nominal line voltage. Sags are further classified by their duration as instantaneous (0.5 to 30 cycles), momentary (30 cycles to 2 seconds), temporary (2 seconds to 2 minutes), and long term (greater than 2 minutes). An interruption is a complete loss of voltage. The same categories used to distinguish the duration of voltage sags are applied to interruptions.

Short duration voltage sags and interruptions are frequently caused by faults on the utility power system. Faults which occur a significant distance from a customer's facility can still result in voltage sags that cause equipment problems. Several on-going and previous studies have been performed to assess distribution power quality (e.g. Allen-Segall (IBM), Goldstein-Speranza (AT&T), National Power Laboratory, and EPRI)^[113,114,168]. The results and measurement techniques of these studies differ in many respects, however, voltage sags were determined to be one of the most likely type of events to occur. It is believed by several power quality experts that voltage disturbances of this type are typically 2 seconds or less in duration. Although EPRI's program to quantify the power disturbance type, duration, frequency of occurrence, and source has not been completed yet, preliminary findings suggest that voltage sags and momentary interruptions are the most frequently occurring events which cause misoperation of sensitive microprocessor-based equipment. Preliminary EPRI data from this on-going study suggests that voltage sags with a magnitude of approximately 80 per cent of the nominal line voltage are common and that the durations of these disturbances cluster in three ranges: 2 to 6 cycles, 30 cycles, and

100 to 150 cycles. This type of data is extremely important for a customer to determine the type of power conditioning equipment required.

Motor starting and the turn-on of other large loads within the customer's facility also cause voltage sags. In many cases, the magnitude of these load variations is not severe enough to cause equipment misoperation, however, the power quality studies performed to date have not determined what percentage of voltage sags (and other disturbances) are caused by utility transmission/distribution faults or operations and what percentage of faults are caused by end-use loads on the customer side of the meter^[116]. This type of study requires simultaneous (and synchronous) monitoring of the customer premise and the utility distribution and transmission system. EPRI plans to expand the scope of their on-going power quality study to analyze the source of power disturbances.

The equipment associated with industrial processes is particularly sensitive to these short duration disturbances. Examples of such equipment include chiller controls, VLSI chip testers, DC drives, programmable logic controllers (PLCs), and machine tools^[136]. DC motor drives are used in many industrial processes such as printing presses and plastics manufacturers; specific models have been found to trip when an 80 per cent voltage sag occurs. PLCs are one of the most important categories of industrial equipment because the entire manufacturing process is often under the control of these devices.

Utilities can apply measures to minimize the frequency of faults on their transmission and distribution systems, however, it is not possible to completely eliminate the occurrence of these faults. Therefore, industrial and commercial customers are beginning considering how to most economically improve the ride-through capability of the sensitive equipment within their facilities.

Impulsive and Oscillatory Disturbances. Impulsive and oscillatory disturbances were identified as the second most important problem associated with commercial and industrial customers. Impulsive transients are characterized as a sudden increase or decrease in the voltage, current, or both; impulses typically contain frequencies greater than 5,000 Hz and have durations of less than 200 microseconds. Oscillatory transients are defined as non-power frequency oscillatory changes in the steady state condition of the voltage, current, or both. This category of transient is further subdivided into three categories based on frequency content:

- High frequency transients have a primary frequency component of greater than 500 kHz with microsecond durations; these transients are due to lightning or the local system response of a switching event. Power electronic thyristor switching together with the R-L-C snubber circuits is one source of oscillatory transients.
- Medium frequency transients have a primary frequency component in the range of 5 kHz to 500 kHz with durations lasting for tens of microseconds. Capacitor switching is often a cause of this type of transient.

- Low frequency transients have a primary frequency component less than 5 kHz and durations on the order of milliseconds. The energizing of a capacitor bank on a utility distribution system is one cause of this transient type.

Although impulsive and oscillatory disturbances are of moderate importance to the commercial and industrial customers, the most frequent problem and associated cause was not readily provided during our customer service interviews.

Waveform Distortion. Waveform distortion was identified as a problem with low to moderate importance relative to the other customer service problems. Waveform distortion is defined as steady state deviations from an ideal sine wave. The five major types of waveform distortion which can be distinguished by their frequency content include harmonics, DC offsets, interharmonics, notching, and electrical noise.

Harmonic current was the waveform distortion type most frequently discussed during our customer service interviews. Harmonic distortion exists due to nonlinear load such as power electronics, ferromagnetic transformers, and arcing devices. These nonlinear loads generate harmonic currents which interact with the power system impedance and cause distortions in the system voltage.

DC offset is the existence of a DC voltage or current in the AC power system and is typically caused by half-wave rectification. This problem can lead to increased transformer saturation and insulation stress.

Interharmonics are sinusoidal voltages and currents with frequencies which are a non-integer multiple of the 60 Hz system frequency. The most common sources of interharmonic waveform distortion include induction motors, cyclo-converters, and static frequency converters.

Waveform notching is defined as a periodic voltage disturbance caused by the normal operation of power electronic devices. Three-phase converters are a common cause of waveform notching. The notches are created when a short duration short circuit exists between two phases during commutation.

Electrical noise is typically defined as unwanted broadband signals with frequency content lower than 200 kHz. This type of disturbance is associated with individual loads within a customer facility and is often caused by improper grounding, switching power supplies, and loads with solid-state rectifiers.

Although our interview results indicate that this disturbance category is not a significant problem, high harmonic currents were reported several times as a waveform distortion problem which resulted in transformer overheating or undersized neutral conductors.

Long Duration RMS Variations & Interruptions. Long duration variations and interruptions include rms deviations outside of the normal ac voltage tolerance for a duration of 2 minutes and longer. This category of disturbance is further broken

down into undervoltages, overvoltages, and permanent interruptions. The results of our interviews, Exhibit 8-1, determined that these type of disturbances are of low importance to most industrial and commercial customers because of their infrequent occurrence.

8.2.2 Improved Energy Utilization

The results of the interview survey indicate that the customer need for improved energy utilization is of low importance relative to power quality problems. In order to assess this need in our interviews, we divided energy utilization into three problem categories: poor power factor, high demand charges, and high on-peak energy charges. These problems are solved by application of capacitors, several types of power conditioning equipment and energy storage equipment. These solutions can be attractive to customers if the proper incentives are provided by demand-side management (DSM) strategies. The most common industrial DSM strategies employed today by utilities are alternative rate designs (i.e. interruptable, time-of-use, and demand period).^[168] The importance of improved energy utilization to an industrial customer depends on the magnitude of the customer's electricity costs compared to his other business costs. For many industries electric energy is not a sufficiently large cost component to make improved utilization a large issue. However, this is not to say electric energy is of little value. Value of electricity to an industrial user is more determined by the costs of power disturbances and interruptions. Power quality and reliability are larger problems to many users than improved energy utilization. Because of its low importance relative to other problems and the limited applicability of micro-SMES technology for end-use, load-leveling functions (which require significant energy storage capability), improved energy utilization will not be considered in the comparison of alternative technologies.

8.3 Evaluation Criteria

In order to assess how well potential solutions solve customer service problems, we selected a set of criteria typically used by commercial and industrial customers to evaluate power conditioning equipment. The criteria were grouped into four categories: technical performance, cost, environmental issues, and risk. The relative importance of each criterion was determined by analysis of the data collected during our interviews. The final weightings used in evaluating the customer service solutions are:

• technical performance,	29%
• cost,	29%
• environmental issues, and	19%
• risk	23%

The Customer Service Criteria Matrix, Exhibit 8-2, provides a ranking and a weighted total for each criterion. These totals were used to establish the final weighting factors for evaluating the alternative customer service solutions. As shown

Exhibit 8-2 Customer Service Criteria Matrix

CUSTOMER SERVICE EVALUATION CRITERIA

WHATs vs. HOWs

Very Important	●●●
Important	●●○
Not Important	○●○

WHATs vs. HOWs		
Very Important	●●●	
Important	●●○	
Not Important	○●○	

		WEIGHT																								
		1																								
		1	TECHNICAL PERFORMANCE																							
		2	LOW COST																							
		3	Equipment Capital Costs																							
		4	O&M/Efficiency																							
		5	ENVIRONMENTAL ISSUES																							
		6	Low EMF																							
		7	Low Noise/Small Size																							
		8	High Disposability																							
		9	RISK																							
		10	Reliability & Safety																							
		11	Technical Maturity																							
		12	Vendor/Supplier Credibility																							
Interview #1	1	1	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	1	
Interview #2	2	1	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	2
Interview #3	3	1	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	3
Interview #4	4	1	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	4
Interview #5	5	1	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	5
Interview #6	6	1	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	6
Interview #7	7	1	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	7
Interview #8	8	1	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	8
Interview #9	9	1	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	9
Interview #10	10	1	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	10
Weighted Total	1		82					90		74			42		42		42				90		46		46	1
Rank	2		3					1		4			7		7		7				1		5		5	2

in Exhibit 8-2, equipment capital cost, reliability and safety, technical performance, and O&M costs were identified as highly important evaluation criteria for the selection of customer-installed, power conditioning equipment. Size, disposal and EMF issues, technical maturity, and vendor credibility were all significantly less important criteria.

8.3.1 Technical Performance Criteria

Technical performance, in general, is an overall measurement of how well the candidate solution meets a set of requirements. For energy storage systems as applied to end-use applications, the major evaluation characteristics include system efficiency, energy density, specific energy, power density, and specific power. Technical performance had the second highest ranking relative to all other customer service evaluation criterion.

8.3.2 Economic Criteria

The economic evaluation criteria considered for end-use applications includes capital cost and operating and maintenance (O&M) costs. Capital costs include all equipment, construction, and labor. Economic justification by return on investment is not commonly employed by industrial or commercial users because the indirect costs (associated with the effect on a purchaser's operations or service) and restart costs are difficult to quantify in many cases. Both capital costs and O&M costs were determined to be very important evaluation criteria to industrial and commercial customers with capital costs ranked the highest of all criterion.

8.3.3 Environmental Criteria

The environmental evaluation criteria includes EMF, noise, size, and material disposal issues. Each of these criterion were relatively unimportant to end-users relative to the high importance of cost, technical performance, reliability, and safety.

8.3.4 Risk

The risk evaluation criteria for end-use equipment includes reliability and safety, technical maturity, and vendor credibility. Reliability and safety was equally as important as capital cost, while technical maturity and vendor credibility was of relatively low importance. All interviewees particularly stressed the high importance placed on safety to personnel in the work place.

8.4 Customer Service Technology Comparisons

Because of the perceived importance of the voltage sag problem relative to the other customer service problems, the following comparison of technologies will focus on the alternative solutions which address only this category of voltage disturbance. For a meaningful comparison of alternative technologies, five energy storage technologies have been selected and configured as off-line standby power supplies. These storage

technologies include lead-acid Starting, Lighting, and Ignition (SLI) batteries, micro-SMES, advanced flywheels, aluminum electrolytic capacitors, and electrochemical capacitors. In order to provide a comparison of micro-SMES to alternative solutions, each system configuration provides a 2 MW rated capacity and a minimum energy delivery capability of 2 MW-sec (or a 2 second supply at 50 per cent of rated load). Each storage technology and its advantages and disadvantages are discussed in the following sections.

Several on-line power conditioning technologies exist which address voltage sags and interruptions which last less than 0.5 seconds (e.g. voltage regulators and motor generators) and significantly longer than 2 minutes (e.g. on-line UPS systems). Large, on-line UPS systems typically provide a 15 minute supply of power for bridging to local, long-term engine generators. Because of their on-line configuration, UPS systems provide other power conditioning benefits such as elimination of harmonics and transients. These power conditioning technologies will be briefly described, however, off-line standby power supply systems which provide a 2 second ride-through capability for 1 to 5 MVA industrial and commercial loads are the primary focus of our technology comparisons.

8.4.1 Batteries

Lead-acid SLI battery technology is available in mature, mass-produced, automotive and traction products. SLI batteries offer a low-cost solution to the voltage sag problem when configured with a properly designed power control system. Based on discussions with a manufacturer of battery systems for load-leveling applications, a 2MVA, 20MJ (10 seconds) system could be provided as a modification to an existing product. The system would incorporate 384 automotive SLI batteries configured as 8 paralleled battery "modules". Each "module" consists of 48 batteries in series and a pulse-width modulated (PWM) converter. The system is sized for a 2 per cent battery discharge. Approximately 30,000 operating cycles is achievable due to the vibration-free, temperature-controlled environment. Therefore, battery life will be limited by shelf-life. Complete replacement of the battery system is required in approximately 5 years at an estimated cost (including labor) of \$33,000. The "maintenance-free" SLI battery system does require hydrogen detection and ventilation equipment to ensure system safety. The storage cost associated with this example system is approximately \$100,000 of which only \$15,000 is associated with the batteries; therefore, energy storage costs are significantly dominated by the containment system. Lead-acid battery and many other types of battery technology are currently being improved and developed for electric vehicle applications.

8.4.2 Micro-SMES (1 MW/1 MW-sec)

Micro-SMES is the only energy storage technology currently being demonstrated to solve the 2 second voltage sag and momentary outage problem. Units with capacities and storage of 750 kW/750 kW-sec, to 1.4 MW/3 MW-sec are commercially available, however, work is in progress on a 2 MW/3 MW-sec system. The major advantages of micro-SMES is its unlimited number of charge/discharge cycles,

modest size and weight, and fast recharge time. The major disadvantages include its high capital and operating costs, and low energy density. The current commercial cost is approximately \$1000/kW (single unit quantity) in the size range previously mentioned. The manufacturer believes that a target cost of \$500/kW (assuming a 1 second system) is achievable in the future with advances in low cost, high temperature superconductors, optimized power electronics, and production quantities of 20 or more per year. Approximately half of the micro-SMES system cost (or \$500,000 for a 2 MW, 1 second system) is associated with energy storage (i.e. cryostat and refrigeration unit). This is approximately 5 times the energy storage cost of the previously described battery system and assumes a factor of 2 reduction in the current micro-SMES selling price. In addition, yearly O&M costs include \$40,000 of refrigeration load and losses in the non-cooled high current path. This cost is based on a 65 kW load for an operational 750 kW-sec, (750 kW/750 kW-sec) system and assumes \$0.07 per kWhr.

8.4.3 Advanced Flywheels

Flywheels are one of the oldest forms of energy storage systems. During the 1970's, several government-sponsored programs investigated advanced flywheel storage for electric vehicle applications. Although government funding ended in the early 1980's, there has been a renewed interest in flywheels for power quality, load-leveling, and electric vehicles. Several U.S. companies (in conjunction with two of the national laboratories which did much of the early flywheel research) are in the early stages of product development. Advanced flywheels or electromechanical batteries (EMBs) potentially offer both high energy density and power density with low cost and minimal maintenance^[105,173.13,173.14,173.15]. Based on discussions with Oak Ridge National Laboratories, the system configured for this comparative analysis provides high energy density by incorporating a high strength, carbon/epoxy composite flywheel driven by an axial air-gap motor/generator at 40,000 RPM within an evacuated containment system. The total cost of this 2 MW/54 MW-sec (15 kWh) system was estimated to be \$700,000 assuming production quantities of 100 per year^[173.14]. Approximately \$200,000 is associated with the energy storage components which include the flywheel, motor/generator, bearing system, and the containment which is sized to ensure safe operation in the event of a catastrophic flywheel failure. Operating costs will be extremely low due to minimal bearing losses (assuming a hybrid active/passive magnetic system) and operation of the flywheel within a vacuum. HVAC equipment is not required, however, a 10^{-5} Torr pressure must be maintained with standard vacuum pump technology. Although early in the development phase, advanced flywheel technology can address the voltage sag problem and is a promising contender for future end-use, load-leveling applications which require significant energy storage capability.

8.4.4 Electrolytic Capacitors

The application of standard aluminum electrolytic capacitors is a technically plausible solution to the voltage sag problem. For comparison purposes, a 2 MW/2 MW-sec system was configured using series/parallel arrangements of approximately 5,400

commercially available computer-grade, 5,600 microfarad, 350 VDC capacitors. The total equivalent capacitance of the system is approximately 25 Farads. Each capacitor module must be properly packaged and fused to ensure personnel safety and reliable operation in the event of a capacitor failure. Based on a capacitor cost of approximately \$35 per device, the energy storage cost of the system including containment and fusing is estimated to be \$240,000 with a total system cost of \$740,000^[173.19]. As shown in Exhibit 8-3, the storage cost per kWh is significantly higher than all other technologies except micro-SMES. The design of a system which incorporates aluminum electrolytic capacitors would require an extensive reliability analysis due to the number of components and connections, the high pulse power application effects, and the operating temperature effects on electrolyte loss. Series/parallel capacitor configurations up to approximately 0.14 Farads are currently found in large UPS systems as a high frequency switch-mode current source for minimizing the voltage distortion due to harmonic loads. However, there is no known manufacturer of electrolytic capacitor bank systems which address the voltage sag and momentary outage problem.

8.4.5 Electrochemical Capacitors

Electrochemical capacitors store energy via a charge separation across a double layer, created by an electrode-electrolyte interface. Extensive development work by the Japanese has resulted in commercial carbon double layer capacitor products which are often referred to as "supercapacitors" or "ultracapacitors." The power density of carbon double layer capacitors is severely limited by the poor conductivity of the composite carbon electrodes. Therefore, a 400 to 600 VDC series configuration of these capacitors for high current applications is impractical. A different type of double layer capacitor, however, has been developed over the last decade for high pulse power military applications. This electrochemical capacitor employs electrodes with a mixed metal oxide ceramic coating which has very low resistivity. As a result, significant power density can be obtained in combination with high energy density. Based on discussions with the U.S. company that developed this technology, the cost of the capacitors, without containment, for a 2 MW/20 MW-sec system was estimated to be \$70,000 assuming volume production quantities of 100,000 units per year^[173.16]. The most likely high volume applications include hybrid SLI batteries, electric vehicles, portable hand-held power tools, and UPS systems for personal computers. If these high volume applications are realized within the next several years, mixed metal oxide double layer capacitors could be an extremely attractive solution for the voltage sag problem by the end of the decade. Other attractive features of this technology include, wide operating temperature range, high cycle life with 100 per cent depth of discharge, and the inclusion of all environmentally benign, non-explosive materials.

8.4.6 2 MW Standby Power System Comparisons

The costs, power, and energy characteristics of the five storage technologies are summarized in Exhibit 8-3 and 8-4. General assumptions associated with these two comparison tables include the following:

- Energy storage technologies/configurations were selected to address only the voltage sag and momentary outage problem. Storage cost is defined as dollars per kWh delivered.
- The total capital cost for each system assumes a 2 MW power conversion system with a selling price of \$500,000 or \$250/kW. The power conversion system cost includes the static switch, control system, inverter electronics, and transformer.
- The technology configurations do not have identical amounts of energy storage due to the design and cost data available.
- The O&M costs associated with batteries do not include battery replacement; for the 2 MW/20 MW-sec battery system, a battery replacement cost of \$33,000 every five years was estimated.
- Total unit costs do not include installation, engineering, and site preparation costs due to their high variability.
- The energy characteristics for each technology are applicable for a short duration (2-second) 2 MW power pulse; these characteristics also take into account the indicated energy utilization percentage.
- For comparison purposes, energy storage volume and weight assumes unpackaged technology (packing factor of 1) except in the case of flywheels for which significant containment is needed for protection against catastrophic failure.
- Each of the five energy storage technologies can be incorporated into a complete system with a volume and weight which would permit a transportable, trailerable product for 2 MJ, 2 MW application.

Exhibit 8-3 2 MW Standby Power System Comparison for Sag Applications

Technology	Delivered Energy/Discharge Period	Total Capital Cost (\$)	Storage Cost (\$/kWh)	O&M Cost (\$/Yr)	Replacement Issues	Storage Size (L) [ft ³]	Storage Weight (kg) [lbs]
Batteries	6 kWhrs/10 secs	\$500K	\$17K	\$15,000	Batteries (5 years)	4,896 [173]	6,982 [15,360]
SMES	.56 kWhrs/1 sec	\$1000K	\$900K	\$68,000	Minimal	3,330 [118]	1,136 [2,500]
Advanced Flywheel	15 kWhrs/27 secs	\$700K	\$10K	< battery O&M costs	Minimal	202 [7]	478 [1052]
Electrolytic Capacitors	.56 kWhrs/1 secs	\$740K	\$430K	< battery O&M costs	Minimal	3,330 [118]	4,633 [10,193]
Electrochemical Capacitors	6 kWhrs/10 secs	\$600K	\$17K	< battery O&M costs	Minimal	298 [11]	835 [1,837]

Exhibit 8-4 Energy Storage Characteristics for Sag Applications

Technology	Delivered/ Total Stored Energy	Energy Density Wh/L [Wh/m ³]	Specific Energy Wh/kg [Wh/lb]	Power Density W/L [W/m ²]	Specific Power W/kg [W/lb]
Batteries	2%	1.2 [33]	.88 [.4]	424 [12,000]	297 [135]
SMES	85%	.17 [4.7]	.50 [.22]	600 [16,950]	1,760 [800]
Advanced Flywheel	75%	74 [2,100]	31 [14]	9,900 [280,500]	4,183 [1,901]
Electrolytic Capacitors	60%	.17 [4.7]	.12 [.05]	600 [16,950]	432 [195]
Electrochemical Capacitors	60%	12 [350]	4 [1.9]	6,711 [18,993]	2,395 [1,088]

8.4.7 Technologies for Momentary Outages

Motor generators, voltage regulators, and active power line conditioners are three technologies which address voltage sags and momentary outages to a more limited extent than the off-line standby power systems previously described. Voltage regulators now employ solid-state techniques which provide a 10 to 12 cycle response time to a step change in input voltage or load.^[166] This type of regulator typically incorporates saturating magnetic material and sensing/control electronics to maintain the output voltage. The speed and energy storage of these devices, however, are insufficient to address severe voltage sags or momentary outages caused by the clearing of utility faults.

A ferroresonant regulator is a second type of voltage regulator which includes a linear inductor and a parallel resonant circuit with a non-linear inductor and a capacitor. This regulating device provides a constant output voltage for a wide range of input voltage. The ride-through capability, however, is limited to approximately 1 cycle due to the small amount of energy storage contained in the resonant circuit. In a three-phase configuration, ferroresonant regulators are referred to as "magnetic synthesizers."

Tap-changing and phase-modulating regulators are two voltage regulator types which can address the majority of voltage problems with the exception of the momentary outage. Tap-changing regulators control the output voltage by thyristor switching of the discrete voltage taps on a power transformer. The response time of this technology is approximately 1 cycle because of the zero current switching requirement of the thyristor. Phase-modulated regulators incorporate thyristors and filters to maintain a sinusoidal output voltage in the presence of nonlinear loads. The output voltage is compared to a setpoint and a voltage is either added or subtracted

with buck and boost transformers and control electronics. A voltage sag up to approximately 50 per cent of nominal voltage can be addressed by fast-response regulator technology.

Active power line conditioners are becoming available with unit ratings up to 150 kVA. These devices employ IGBT semiconductor technology using pulse-width modulation (PWM) techniques to inject equal but opposite harmonics into the customer's distribution bus. This technology neutralizes harmonics created by nonlinear loads, isolates the upstream network from the load's "pollution", and can correct poor power factor caused by phase shifts between load voltage and current. Similar to fast-response regulators, active power line conditioners can eliminate severe voltage sags (50 per cent of nominal line) but cannot prevent momentary outages unless an energy storage device is added.

Motor-generator (M-G) sets completely isolate the load from the power line and therefore provide significant on-line benefits. This type of equipment consists of an AC or DC motor which drives an AC generator. Motor-generator sets provide protection against voltage sags and sustained undervoltages by regulating output voltage within 3 per cent when input voltage drops as much as 22 per cent. In addition, the rotating inertia is used to "ride-through" total loss of power for approximately 0.3 seconds in larger units (500 kVA). This time is limited by the drop in output frequency as energy is removed. For smaller units, flywheels are often added to increase the amount of stored kinetic energy and this extends the outage ride-through time to approximately 2 seconds. Batteries are often used to extend the protection period so that backup generation can be started for longer term operation. For computer loads, a typical configuration includes an off-line, solid-state inverter, rectifier/charger, and battery bank used to drive an AC synchronous motor and generator. End-to-end efficiencies of 90 per cent or greater are achievable at 40 to 100 per cent of rated load. The equipment cost for a 500 kVA unit is approximately \$63,000 with a size of 340 ft³ and weight of 13,000 pounds. M-G set technology is very mature and reliable (250,000 hour MTBF), however, the ride-through times are normally insufficient for starting back-up generation or controlled shutdowns. Furthermore, M-G sets do not eliminate momentary outages longer than 0.5 seconds.

8.4.8 UPS Systems

Large (greater than 500 kVA), on-line battery UPS systems are commonly employed to provide 5 to 30 minute backup power for critical loads while continuous diesel generation is started. Significant additional benefits associated with this type of equipment include protection against voltage sags, swells, and transients as well as continuous regulation of voltage and frequency. A comparison of on-line battery UPS with off-line micro-SMES is not very practical because of the difficulties in quantifying the dollar value of on-line power conditioning benefits. However, other than micro-SMES technology, large on-line battery UPS systems are the only commercially available products which solve a voltage sag problem which lasts approximately 2 seconds with a 1 MVA load.

The large static UPS systems are offered by several manufacturers, however, only on-line configurations are available as standard product. A representative 2 MVA system with 10 minutes of backup (333 kWh) would consist of two 1 MVA systems connected in parallel with bypass switchgear. The total (uninstalled) 2 MVA system cost including batteries is approximately \$600,000 (or \$300/kVA) excluding installation, site preparation, HVAC equipment, or engineering costs. Battery costs and the bypass switchgear are approximately \$160,000 and \$100,000, respectively^[173.11]. If one assumes an inverter efficiency of 93 per cent, a 1 MW load, and \$0.07 per kWhr, parasitic losses result in an annual operating cost of \$613,200. Battery inspection, periodic monitoring, and replacement, environmental conditioning, and the building maintenance associated with the large footprint requirements, add significantly to the O&M costs. The battery size and weight associated with a 5 to 30 minute backup requirement for a 2 MVA load can significantly increase installation costs, particularly in installations above the ground floor of a facility. In these cases, structural reinforcement and rigging costs in excess of \$200,000 are possible. Therefore, the high cost of operation and installation are the main reasons why on-line UPS systems greater than 500 kVA are not typically installed for power conditioning benefits alone. It is for this same reason that a market niche may exist for a large off-line UPS system which employs one of the five identified energy storage technologies. Today, only micro-SMES technology is filling this niche in the form of a product designed specifically for addressing the 2 second (or less) voltage sag problem within the industrial and commercial market sector.

Based on several discussions with UPS sales personnel, small (less than 10 kVA) UPS systems are beginning to be applied in a distributed fashion within manufacturing facilities^[173.11]. A typical cost for a 4.3 kVA unit with 10 minute backup is approximately \$5,000. These small UPS units are beginning to be used to condition the power for individual programmable logic controllers (PLCs).

8.5 Analysis of Alternative Solutions

The analysis of energy storage technologies as applied to off-line standby power systems for end-use applications is summarized in Exhibit 8-5. The ranking and weighted total provide a relative indication of how well, when all evaluation criteria are considered, each technology addresses the 2 second (or less) voltage sag problem.

The general conclusions which can be drawn from this analysis and the comparison of alternative solutions include the following:

- All five energy storage technologies can be applied in a practical manner to achieve the 2 MJ (minimum), 2 MW technical performance requirements.
- Due to the importance of low initial capital cost for customer acceptance, systems which incorporate high-volume automotive or traction SLI battery technology will have a dominate share of this market niche by the year 2000. Based on the automotive industry's ability to recycle lead-acid batteries, the disposal issue is not seen to be a significant problem in the future. However, the cost of battery

maintenance and replacement will provide incentive for the continued development of flywheels, micro-SMES, and electrochemical capacitors.

- Although no known commercially available product exists today which competes directly with micro-SMES technology (e.g. designed specifically to eliminate only short duration voltage sags), several U.S. companies may develop systems which incorporate advanced flywheels, conventional SLI battery technology, or electrochemical capacitors.
- The major disadvantage of micro-SMES technology relative to alternative energy storage technologies is its high capital and operating costs. These high costs, together with the potential near-term application of small (less than 50 kVA), distributed conventional UPS technology, will significantly limit the micro-SMES market share in the year 2000 time frame. The number of micro-SMES units sold before the end of the decade will also depend on how quickly competing solutions become proven in field demonstrations.
- In the time frame surrounding the year 2030, improved batteries and advanced flywheels will be the likely technologies used to address the long term need for end-use, load-leveling. The market penetration of one or both of these technologies will be determined primarily by cost. Therefore, market share will be closely linked to the level of adoption in high volume applications such as the electric vehicle and the associated infrastructure equipment (e.g. charging systems).
- By the year 2030, micro-SMES technology is not likely to compete with other storage technologies (which are characterized by high energy densities) in end-use, load-leveling applications due to its high energy storage and operating costs. There appears to be no high volume application of micro-SMES technology on the horizon which could significantly drive the system cost down to a level competitive with other storage technologies which are more suitable for high volume applications. The application of high temperature superconductor (HTS) to micro-SMES is not likely to provide the significant performance and cost improvement required. Application of HTS technology to current limiters, motors, or generators is not expected to drive the cost of HTS down sufficiently to make micro-SMES more competitive. Furthermore, micro-SMES market share is further reduced within this time frame due to improvements in the ride-through capabilities of equipment used in critical processes and services.

The near-term (year 2000) conclusions are based on the assumption that solving only the 2 second voltage sag problem has significant benefit to industrial and commercial customers. Today, there is insufficient information on the voltage sag problem with respect to frequency of occurrence, duration, equipment affected, and the cost to relevant industry segments. Therefore, additional analysis of statistically valid power quality data, focussed market studies, and development of cost (or benefit) models for appropriate industries will be necessary to verify and quantify the need for large, off-line standby power systems which address short duration voltage sags.

Exhibit 8-5 Customer Service Technology Competitiveness Matrix

CUSTOMER SERVICE ANALYSIS

Evaluation Criteria vs. Alternative Solutions

WHATs vs. HOWs							
Strong Characteristic	●	9					
Average Characteristic	○	5					
Weak Characteristic	○	1					
	WEIGHT	Batteries	SMES	Advanced Flywheel	Electrolytic Capacitors	Electrochemical Capacitors	
TECHNICAL PERFORMANCE							
Power Quality (voltage sag < 2 secs)	30	●	●	●	●	●	
LOW COST							
Equipment/Capital Costs (within 5 yrs)	20	●	○	○	○	○	
O&M/Efficiency	10	○	○	●	●	●	
ENVIRONMENTAL ISSUES							
Low EMF	5	●	○	○	○	○	
Small Size/Light Weight	10	○	○	●	○	●	
Minimal Disposal Problems	5	○	●	●	○	●	
LOW RISK							
Reliability & Safety	10	○	●	○	○	○	
Technical Maturity	7	●	○	○	●	○	
Vendor/Supplier Credibility	8	●	○	○	○	○	
Weighted Total		765	617	625	613	625	
Rank		1	4	2	5	2	

The longer term (year 2030) conclusions are based upon the observation that an increasing number of utilities are focussing on DSM as a capacity planning resource. As utility alternatives for increasing capacity become limited, future industrial DSM programs may provide greater incentives for customers to install storage technologies with load-leveling capability.

9.0 Benefit/Cost Comparison for SMES Applications

9.1 Background

The ratio of life-cycle benefits to life-cycle costs can be a useful measure of the attractiveness of technologies which offer the potential for more than a single type of benefit to a utility's system. Using benefit/cost ratios, a technology's value to a utility is determined by comparing the total projected benefits to the total projected costs for a particular application. Technologies which have ratios greater than 1.0 are considered to be potentially attractive for application.⁵

In order to objectively perform this analysis, all of the potential benefits offered by a technology must be accounted for. Typical benefits might include avoided investment in new generation resources, avoided or deferred transmission and distribution system upgrades and additions, improved operating efficiency, emissions reductions, and power quality improvements. Benefits are not all additive and must be considered separately for a given application and site.

The applications of energy storage technologies like SMES can be categorized as providing either bulk storage capacity (e.g., diurnal storage) or short-term dynamic storage. Strategic applications are often referred to as a third category, however, most of the benefits in these applications are derived from bulk storage capacity, e.g., to reduce emissions, reduce outages, or reduce exposure to fuel price fluctuations and fuel availability constraints. Bulk storage benefits might include avoided investments in new or upgraded generation, transmission, or distribution capacity. Dynamic storage benefits could include load regulation, operating reserve, and power quality control. The range of benefits which may be applied will depend on the characteristics of the energy storage device and the nature of a particular application. Technologies which provide low-cost, large capacity energy storage capability will often be preferred in bulk storage applications. Technologies with better response characteristics will tend to be favored in applications needing dynamic storage.

9.2 Benefits for SMES and Other Technologies

The benefits from applying SMES and competing technologies in specific applications are very dependent on individual utility system needs. For this reason there is a range of possible benefits which may be derived from a given type of SMES application. Several studies of SMES benefits have listed many possibilities and have attempted to quantify them.^[9,15,16,17,21,49,133] Benefit analysis related to some of the applications proposed for SMES has also been performed for a number of other emerging technologies, such as batteries, fuel cells, and photovoltaics.^[80,81,92,94,175,176,177,178,186] For purposes of this analysis we have grouped benefits into three major areas:

⁵ Although some utilities desire benefit/cost ratios much greater than 1 (e.g., 3 or greater) to ensure the economic attractiveness of a technology.^[171]

- generation,
- transmission and distribution (T&D), and
- customer service.

The transmissions and distribution benefits have been grouped together because of the similarity of benefit descriptions. The customer service segment also includes applications where devices are installed at the distribution level for customer-related power quality needs.

9.2.1 Generation Benefits

Generation benefits include those from bulk storage applications as well as dynamic storage applications. Diurnal storage benefits typically require sufficient storage capacity to allow 1-8 hours of use. Dynamic benefits may be obtained with storage capacities of several seconds to several minutes.

Bulk Storage Capacity Benefits. Possible bulk storage benefits for generation include:

- *Peak Load* - the ability to provide power during the peak demand period of the day.
- *Energy Storage Savings* - storage of lower cost electricity generated during light load periods to displace more expensive generation during peak load periods.
- *Reserve Margin* - the ability to displace a combustion turbine, for example, in helping to control, in accordance with pool criteria, the probability of disconnecting load due to a generation deficiency at a time of annual peak.
- *Modularity and Short Construction Times* - the capability to build the storage resource in small capacity increments and disperse them within the utility's system as well as the ability to design, site, and construct units in a short time period.
- *Black Start Capability* - a generation resource has black start capability if it can begin generating power without the use of external (i.e. start-up) power supplied from the grid.
- *Environmental Benefits* - by using storage effectively, generation units can be run more efficiently, and operation of older, less efficient plants which generate more pollution may be decreased.

Dynamic Storage Benefits. Possible dynamic storage benefits for generation include:

- *Operating Reserve (includes spinning reserve)* - capacity which allows a generation system to recover rapidly from unexpected load increases or equipment failures. Often divided into two parts, primary reserves and secondary reserves. Primary reserves are capacity which is available to respond to instantaneous emergencies such as unit tripping or loss of imported power. This could be either spinning (synchronized) or capable of quick start (nonsynchronized). Secondary reserves are typically available in 30 minutes for responding to less severe impacts such as load forecasting error. Savings are also attributed to thermal start-ups avoided.

- *Load Following* - the ability of a generation or storage unit to follow system load changes instantaneously, which allows other generation units to run at constant and more efficient set points.
- *Ramping* - the response rate of a generation unit is defined as its ability to follow the instantaneous changes in chronological load. Unit ramping capability depends on the unit ramping mode (decreasing or increasing) and the unit loading. SMES would discharge to supply the load during ramp-up and recharge during ramp-down periods. This would allow for more efficient stepping of system generation in large blocks when desired.
- *Automatic Generation Control* - utilities attempt to maintain area control error within predefined bounds. Fast load changes, loss of generation capacity, and failures in the transmission system cause a response from the generation equipment. The amount of on-line load pickup and rejection capability affects dispatch decisions, which in turn affects system overall operating costs. Dynamic storage benefits include modifying the dispatch order to lower system operating costs.
- *Frequency Regulation* - the ability of an interconnected system of generating units to regulate frequency during changes in load and generating unit operation. Dynamic storage can help to dampen frequency oscillations minimizing the need for generator control systems to constantly adjust for load variations. This can reduce wear and tear on generation equipment and decrease maintenance costs.

Information on the range of potential benefits for generation appears in Exhibit 9-1. For purposes of comparison we have converted the annual benefits into a normalized value in \$/yr/kW. We have also indicated the potential high and low range of benefits which may exist. An estimate of the likely magnitude of combined bulk and dynamic storage benefits has also been provided to indicate the potential total (dynamic and bulk storage) range of benefits in any one location. It is important to note that these benefits are not always additive for all generation systems and applications. They are very dependent on the specific SMES size and utility system generation needs.

Some benefit analyses that have been performed for SMES or other technologies have estimated specific benefits which fall outside the range of benefits reported in this analysis. We attribute these values to definitions which include more than one benefit. Spinning reserve, for example has in some cases been defined to also include load following, ramping or frequency regulation. The dynamic benefit of spinning reserve includes operating cost savings and avoided start-up of other units. The capacity benefit of having this resource available is included as part of the bulk storage benefits. The avoided capacity savings is not included in our definition of spinning reserve benefits to avoid double counting.

Exhibit 9-1 Range of Potential Generation Benefits⁽¹⁾

Generation Levelized Annual System Benefits	
Bulk Storage Capacity Benefits	\$/yr/kW
Peak Load	4 - 65
Energy Storage Savings	1 - 48
Reserve Margin	5 - 14
Modularity/Short Construction	2 - 4
Black Start	1 - 3
Environmental	<u>0 - 5</u>
Potential Range (all benefits may not be additive)	13 - 139
Dynamic Benefits	\$/yr/kW
Spinning Reserve	2 - 20
Load Following	1 - 20
Ramping	4 - 10
Automotive Generation Control	0 - 20
Frequency Regulation	<u>3 - 8</u>
Potential Range (all benefits may not be additive)	10 - 78
Combined Storage and Dynamic Benefits	\$/yr/kW
(Storage Benefits + 50% Dynamic Benefits)	18 - 178

(1) ADL estimates based on reference 3,15,16,17,18,21,35,49,71,76,80,81,94,133,175,176,177,178,185. Many of the studies which have been performed have focused on the ETM or larger sized diurnal storage applications. [9,15,16,17,21,35,49,71,76,133] For these studies efforts have been made to find locations where maximum benefits can be obtained. There is a need to perform studies on applications with dynamic operating benefits which require less storage capacity.

9.2.2 Transmission and Distribution

Transmission and distribution applications require primarily dynamic storage but some applications may have bulk storage benefits as well.

Bulk (Diurnal) Storage Capacity Benefits. Possible bulk storage benefits for transmission and distribution may include:

- ***Deferred Transmission and Distribution Investments*** - use of storage to schedule loading of existing T&D lines can help to defer the need for T&D upgrades and additions.
- ***Lowered Resistive Losses*** - locating energy storage devices near load centers allows energy to be transmitted off-peak when transmission losses are lower.
- ***Area Protection*** - energy storage devices located near load centers may help to decrease the need for redundant transmission line capacity in remote areas by providing energy during short and prolonged outages.

Dynamic Benefits. Possible dynamic storage benefits for transmission and distribution may include:

- ***Voltage Regulation (VAR Control)*** - dynamic storage devices can decrease the need for voltage control, control of reactive power (VARs) or power factor correction typically accomplished by accomplished by transformers or special equipment such as static capacitors/reactors or synchronous condensers.
- ***Transient Stability*** - storage devices can help maintain system stability through periods of major system disturbance (i.e. loss of major generation, transmission, or load components).
- ***Steady State Stability (System Stability)*** - storage devices can help maintain system stability by damping low frequency power oscillations allowing more efficient generator control schemes by decreasing short duration load variations.

The range of values for these potential transmission and distribution benefits is summarized in Exhibit 9-2. An estimate of the likely magnitude of combined bulk and dynamic storage benefits has also been provided to indicate the potential total (bulk and dynamic storage) range of benefits in any one application. As was the case for the generation applications, the specific transmission and distribution benefits obtained are very system and application specific.

9.2.3 Customer Service Benefits

Benefits may be derived from technologies which target the customer service market segment by placing them either at the distribution level or at the customer location. The power output and storage characteristics may vary slightly due the load being serviced, but the SMES characteristics will generally be similar.

Bulk (Diurnal) Storage Capacity Benefits.

- ***Reduce the Number and/or Duration of Interruptions*** - improved reliability of service to customers by providing storage near the load in the distribution system or at the customer location.

Exhibit 9-2 Range of Potential Transmission and Distribution System Benefits⁽¹⁾

Bulk Storage Capacity Benefits	\$/yr/kW
Deferred T&D Investment	12 - 13.4
Lower Resistive Losses	6 - 10
Area Protection	<u>1 - 10.5</u>
Potential Range (all benefits may not be additive)	19 - 34
Dynamic Benefits	\$/yr/kW
Voltage Regulation	1
Transient Stability	5 - 20
System Stability	<u>0 - 3</u>
Potential Range (all benefits may not be additive)	6 - 24
Combined Storage and Dynamic Benefits	\$/yr/kW
(Storage Benefits + 50% Dynamic Benefits)	22 - 46

(1) ADL estimates based on references 3,15,16,17,18,21,35,49,71,76,80,81,94,133,175,176,177,179,185

Dynamic Benefits.

- ***Improve Power Quality*** - provide protection from voltage fluctuations, low-frequency harmonics, transient overvoltages, and helps to minimize interruptions.

The range of benefits which have been attributed to customer service technologies is extremely broad.^[3,146,147,148] Additional effort is required to better determine the actual value these devices will have to customers either through decreased interruptions or improved productivity. Based on the analysis conducted in Section 8, it would appear that interruptions of 1-10 seconds account for a significant portion of the benefits in this segment. In order to obtain significant additional benefits, several minutes to over an hour of storage capacity will be required.

From the available information and various discussions with individuals working on quantifying benefits of improved power quality, we have calculated a range of likely benefits for customer service applications. Exhibit 9-3 defines the range of benefits for storage applications as well as dynamic applications. Bulk storage benefits are based on the avoided cost of having alternative power generation capacity. The dynamic benefits are based on information on the potential costs of interruptions.^[145,146,147,3,173.1,173.3,173.4,180] A significant range in values exists and it is not clear that customers are willing to pay to avoid interruptions at even close to the estimated value.

Exhibit 9-3 Range of Potential Customer Service Benefits ⁽¹⁾

Customer Service Levelized Annual System Benefits	
Bulk Storage Capacity Benefits	\$/yr/kW
Avoided cost of backup generation	0 - 200
Dynamic Benefits	
Power Quality (based on cost of interruption)	14 - 150
Potential Range (benefits added at full value)	14 - 350

(1) ADL estimates based on references [145,146,147,3,173.1,173.2,173.3,173.4,173.14,180]

9.3 The Impact of Coincidence of Benefits Across Problem Areas

Many of the studies which have been performed for SMES have focused on the coincidence of benefits resulting from solving a number of different applications problems from a single installation. This includes benefits for generation capacity, energy storage, spinning reserve, load following, deferred T&D investments, transmission line stability, etc. By taking advantage of this opportunity for coincidence of benefits, many studies have indicated that substantial benefits may be obtained which will make SMES and other emerging technologies even more attractive. The location of the device determines how the benefits may be applied. Exhibit 9-4 indicates the flow of potential coincident benefits within a utility's system.

Exhibit 9-4 Flow of Potential Benefits for SMES Applications

The dynamic benefits of technologies can frequently be obtained from devices installed primarily for capacity benefits. However, devices installed for dynamic benefits do not typically have adequate energy storage to provide storage capacity benefits. If the storage is added, the capital cost is increased dramatically. In Exhibits 9-1 and 9-2 a combined benefit has been calculated which is based on adding 50% of the dynamic benefits to the capacity benefits associated with a bulk storage application. It is, of course, difficult to generalize about the degree to which these benefits will be additive, since this will vary from site to site. However, 50% is indicative of the fact that not all the dynamic system benefits, such as transient stability control, will be provided by a single device which is being used primarily for a bulk storage application.

An energy storage device may be sited such that it provides both generation benefits and T&D benefits. If located correctly at the transmission level, for example, it may produce reserve margin, peak load capacity, and energy storage benefits in addition to benefits of deferred T&D investment, lowered resistive losses and area protection. It is also possible that several of the dynamic benefits from both the generation level and the T&D level may be included. For simplicity we have taken the combined generation benefits and added 50% of the combined transmission benefits to obtain an approximation of the total system benefits. For dynamic storage applications we have taken the dynamic benefits at the generation level and added 50% of the dynamic benefits at the transmission level. These two combinations yield leveled annual system benefits of:

- Combined generation and T&D storage and dynamic benefits 29-201 \$/kW/yr
- Combined generation and T&D dynamic benefits 13-90 \$/kW/yr

A more rigorous accounting of what portion of the benefits may be additive in site specific situations is required in order to better evaluate overall benefits in these applications.

It does not appear that benefits at the customer service level are additive to benefits at the utility system level. Devices applied at the customer service level primarily provide reliability or enhanced power quality for the customer. For this reason, we have not added utility system benefits to customer service benefits.

9.4 Comparison of Benefit/Cost Ratios

Benefit/cost ratios combine the estimates of the benefits as discussed in Sections 9.2 and 9.3 with estimates of total annual system costs. The objective in calculating these ratios is to determine if the range of potential benefits is larger than the cost (i.e. benefit/cost ratios greater than one). In order to calculate benefits and costs for representative SMES systems we selected sizes characteristic of typical utility applications and determined benefits for these typical applications for each major category of benefit. These systems are defined below.

<u>Application</u>	<u>Typical Size</u>
Generation:	
• Bulk storage capacity benefits	1000 MW/4000 MWh
• Dynamic storage benefits	400 MW/20 MWh
Transmission and distribution:	
• Bulk storage capacity benefits	10 MW/40 MWh
• Dynamic storage/benefits	400 MW/400 MW-sec
End Use:	
• Dynamic storage applications	1 MW/1 MW-sec

Cost estimates are based on the mid-range of the cost projections from Section 4.

Exhibit 9-5 summarizes the comparison information used for determining the range of possible benefit/cost ratios. Ratios are presented for year 2000 and year 2030 applications. The benefit/cost information is presented in graphic form in Exhibit 9-6. This shows the relationship between benefits and system costs as storage requirements increase, and as a function of system size. As storage capacity increases, cost is increasing at a faster rate than the associated benefits. Based on this trend, it appears that favorable benefit/cost ratios are more likely in applications requiring less storage on a kW energy basis (<10 kW-sec). For this reason, small, distributed storage applications (10 MW/1 MWh) do not appear to be very attractive. There is more potential for small systems which require very little storage. These systems take advantage of the reliability benefits which can be quite high.

It appears that some transmission system applications requiring dynamic storage may have favorable benefit/cost ratios. Typical sizes for this application would be 400 MW/400 MW-sec. These applications have benefit/cost ratios exceeding 2 by the year 2030 which indicate they are potentially attractive.

It also appears that there is the potential for favorable benefit/cost ratios for systems of 400 MW/20 MWh in generation applications when benefits are available from the transmission system. These additional benefits help to push the benefit/cost ratio over 1 in the year 2000 and over 3 by the year 2030 in some cases. Based on generation system benefits alone, it may be more difficult to obtain favorable benefit/cost ratios for systems of this size.

Exhibit 9-5 Comparison of Potential Benefit/Cost Ratios

Application	Size MW/MWh	Levelized Annual Range Benefit \$/kW/yr	Year 2000		Year 2030	
			Levelized Annual Cost (\$/kW/yr)	B/C (Range)	Levelized Annual Cost (\$/kW/yr)	B/C (Range)
Generation						
Storage	1000 MW/4000 MWh	13 - 139	600	.02 - .23	300	.04 - .46
Dynamic	400MW/20 MWh	10 - 78	56	.2 - 1.4	28	.4 - 2.8
Combined	1000 MW/4000 MWh	18 - 178	600	.03 - .3	300	.06 - .6
Transmission/Distribution						
Storage	10 MW/40 MWh	19 - 34	3,300	<.01	1,650	.01 - .02
Dynamic	400 MW/400 MW-sec	6 - 24	21	.3 - 1.1	11	.6 - 2.2
Combined	100 MW/400 MWh	22 - 46	1,300	.02 - .04	650	.04 - .07
Combined Generation Storage and T&D Benefits						
	1000 MW/4000 MWh	29 - 201	600	.05 - .4	300	.1 - .8
Combined Generation Dynamic and T&D Benefits						
	400 MW/20 MWh	13 - 90	56	.3 - 1.6	28	.5 - 3.2
Customer Service						
Storage	1 MW/1 MWh	0 - 200	4000	0 - .05	2,000	0 - .1
Dynamic	1 MW/1 MW-sec	14 - 150	100	.1 - 1.5	50	.3 - 3.0
Combined	1 MW/1 MWh	14 - 350	4,000	0 - .1	2,000	0 - .2

Exhibit 9-6 Range of Possible Benefit/Cost Information

On the basis of benefit/cost information, it appears that systems with large amounts of storage such as the 1000 MW/4000 MWh generation bulk storage application may be more difficult to justify. Significant cost reductions (on the order of 50%-75%) or substantial additional benefits must be identified to obtain favorable benefit/cost ratios. The opportunity for very large additional benefits is considered unlikely except in a very limited number of unique applications.

9.4.1 Limitations of Benefit/Cost Ratios

Although benefit/cost ratios can provide a simple means for evaluating the attractiveness of new technologies, their use has certain limitations. As has been noted, there is considerable variability and uncertainty in both the benefits and the costs of SMES technology. Costs are always best known and supported by actual design, construction, and operating experience. Benefits can be difficult to quantify, even with an existing operating unit, as is evidenced by difficulties in defining and measuring the dynamic operating benefits of existing pumped hydro units^[92]. Thus, the significance of benefit/cost evaluations must be carefully interpreted in light of the maturity of the technology and the inherent complexity of power system operating economics.

Although benefit/cost ratios may be a useful screening tool for understanding trends for competing technologies, they must be used with caution for evaluating the true effectiveness of a potential investment. Utility investments are typically judged on the basis of comparisons of least cost alternatives and minimum impact on rate payers. Ultimately, investment options which will allow the utility to become more competitive will be selected.

10.0 Market Projections for SMES and Competing Technologies

10.1 Introduction

In the following sections we evaluate the market for SMES and competing technologies in each of the four market segments (generation, transmission, distribution, and customer service). For each segment, the market for equipment is considered in the year 2000 and the year 2030. General market trends are considered and the total need for new equipment is assessed; the potential market for SMES is then estimated.

10.1.1 Demand Growth

The need for SMES-like devices in all four market segments: transmission, distribution, and customer service is ultimately driven by increases in the demand for electricity. The demand for electricity is currently expected to grow at an annual rate of 0.9-1.5 percent per annum over at least the next two decades. This represents a significant reduction from the 6-8 percent growth rates of the 1960's and 1970's. Exhibit 10-1 below shows the projection for electricity demand growth over the next ten years as presented by NERC in their 1992 annual outlook for electricity. Longer term projections for electricity demand growth generally agree that the rate of growth in demand will remain relatively constant between 0.9-1.5% slightly.^[142,158] This

Exhibit 10-1 U.S. Summer Peak Demand (Thousands of MW)

relatively low rate of growth is due to a number of factors, such as increased focus on energy conservation and demand side management (DSM), and relatively slower rates of economic growth. New uses of electricity, such as heat pumps and other new end-use technologies may help to increase demand for electricity to some degree, however, these factors are not expected to have a major impact on growth rates.

The market for SMES technology is also influenced by the size of the market for new and replacement power generation, transmission and distribution equipment. The market for power generation and electrical equipment is influenced by the rate of retirement or replacement of existing equipment. Over the next twenty years or so replacement is expected to contribute only moderately to the demand for new equipment. From the year 2010 through 2030, however, it is possible that a significant portion of the existing power generation, transmission and distribution infrastructure will be replaced or refurbished.

The significance of the impact of accelerated retirements on SMES markets is that capacity addition trends beyond the year 2010 will have the potential to create a more attractive market for energy storage. The underlying driver for utilities in the technology selection process will be competitiveness. Utilities will increasingly find themselves in a more improving overall competitive environment. Technologies which assist them in achieving this goal will be required.

10.1.2 Cost Distribution

Of the four market segments, generation currently absorbs the major portion of both capital and operating expenditures. Exhibit 10-2 indicates that approximately 65 percent of the total owning and operating costs for utilities are for generation (59% of capital plus 70% of O&M). Distribution requires approximately 17 percent of the total capital investment and O&M cost. Transmission investment accounts for only 7% of the total. Other expenses, 11% of the total, include costs of administration, offices, repair facilities, equipment, accounting and other miscellaneous expenses.^[188,189]

It is helpful to understand this distribution of expenditures between market segments in considering the market potential for SMES. Based on historical data, this pattern of investment and operating expense is likely to remain fairly constant in the future.

10.2 Generation Market

The total market for new generation equipment is driven by the underlying demand for electricity and the rate of capacity replacement. The type of new generation capacity (base, intermediate or peak-load) which will best meet an individual utility's needs will vary for each utility based on regional demand profiles and the nature of existing capacity. SMES has the potential to displace some of these peak generation capacity requirements.

Exhibit 10-2 Investor-Owned Electric Utility Cost of Service Allocation

Exhibit 10-3 compares various forecasts for generation capability in the U.S. for the years 2000 and 2010. Estimates for the year 2030 are based on maintaining the 2000-2010 growth rates. It is expected that non-utility generators (NUGs) will contribute approximately 50% to this total over the time period. Adjusting the growth rates results in a one percent per year average growth to be supplied by utility-owned generation. The requirement for new resources is based on this increase in capability and any replacements required for retirements.

Much of the existing installed capacity will be 40-50 years old and will require significant upgrade or replacement. The size of the replacement market has the potential to approach the requirement for new capacity to support demand growth by the end of the forecast period. Exhibit 10-4 indicates the impact on the replacement market of increasing from the current level of 2-3000 MW/yr. or replacement to 10,000 MW/yr.

Exhibit 10-3 U.S. Electric Utility Generating Capability Forecasts (GW)

Agency or Organization		Forecast Year				Net Summer Capability Incl. NUGs ⁽¹⁾		Growth Rate ⁽²⁾ (%/yr)
		1990	2000	2010	2030	2000 ⁽²⁾	2030	
DOE/EIA	Net Summer Capability (Excl. NUGs) ↑	690	720	789	947	0.9%	805	1174
		690	716	766	877	0.7%	793	1038
		690	713	744	810	0.4%	786	907
		690	727	—	—			
NERC	↓	690	727	—	—			
NERA		690	791					
WEFA	Net Summer Incl. NUGs	710	745	880	1228	1.7%		
GRI	Nameplate Capability (Excl. NUGs) ↑	770	808	828	889	0.24%		
DRM/McGraw-Hill		770	823	920	1149	1.1%		

- (1) Assumes NUGs will contribute 50% of new capacity. Source: Annual Energy Outlook 1993 (AEO93)
 (2) Growth rates for 2000-2030. DOE/EIA - 0383 (93) January 1993
 (3) AEO93, Tables A5, B5, C5. Table 21, page 78.^[142]

Exhibit 10-4 Impact of Accelerated Capacity Retirement Rate Past Year 2010

10.2.1 Generation Market Trends

Year 2000. Over the next ten years it is expected that 90-100,000 MW of generation capacity (10,000 MW/yr.) will be added in the U.S. Of this, it is anticipated that approximately 50 percent will be owned by NUGs. Based on historic trends annualized capital expenditure is approximately \$50 billion for generation (see Exhibit 10-2). Due to a current excess of baseload capacity, it is expected that 20-30 percent of the total need for new capacity (2-3000 MW/yr) will be for peaking. Exhibit 10-5 shows the 1992 capacity mix and the planned capacity additions for the next ten years. In the current planning by utilities, it is expected that up to one quarter of the need for new peaking capacity (500-750 MW/yr) will be met by bulk power storage technologies.^[158,170] Most of this capacity will likely be pumped hydro, with a small percentage of CAES systems later in the time period.^[169]

Exhibit 10-5 U.S. Utility New Peaking Capacity Needs

Year 2030. Based on the projections of demand growth for the post 2000 timeframe in Exhibit 10-3, as much as 200-300 GW of new capacity may be required during this 30 year period. Given that 50 percent or more of the existing generation capacity in the U.S. is more than 30 years old, it is possible that as much as 50 percent or more of the current capacity will require replacement by the year 2030. This may result in a requirement for up to 200-300 GW of replacement capacity in addition to the need for 200-300 GW of new capacity. The total capacity requirement (replacement plus new) could then reach 400-600 GW over the 30 year

period or 13-20 GW per year. Several studies have indicated that bulk storage of 5-10 percent may be effectively used on many systems.^[88,42,131,135,164] This would equate to an annual bulk storage requirement of 650-2000 MW per year in the post 2000 timeframe.

10.2.2 SMES Generation Market Penetration

Year 2000. Based on the economic analysis of energy storage technologies performed in Section 4, SMES does not appear to offer sufficient benefits to offset its high costs in this medium term time frame. The generation market applications require significant amounts of energy storage which may be obtained with a number of alternative technologies at substantially lower costs. Any opportunity for SMES will require sufficient external incentives to lower the apparent cost to be competitive with these competing technologies. The only likely generation application in the year 2000 market will be for demonstration purposes.

Year 2030. The major application for energy storage technologies in the generation market in the year 2030 will be based on the need for peaking capacity and diurnal storage. Based on our analysis in Sections 4 and 5, SMES does not appear to have the potential to be generally competitive in this application. Significant additional cost reductions will be required in order for SMES to compete as is illustrated in Exhibit 5-7.

An opportunity for SMES in the post 2000 timeframe generation market may exist based on the need for its dynamic characteristics. This requirement would be for units of 100-400 MW in power output with 10-50 MWh of storage capacity for integration of bulk power supply. Based on the potential costs of SMES systems and batteries (Exhibit 4-10), it is possible that SMES will be competitive in this market. The number of potential applications for these devices will depend upon how the utility market evolves. Increased transmission system access, more NUGs, and the emergence of distributed generation may lead to problems of control, which could provide opportunities for SMES in this application. Our analysis suggests that this market will be shared by a combination SMES and batteries. The need for this type of technology relative to total system capacity has not been determined. To achieve a ratio of 1% approximately 2 - 3 applications per year (1000-1500 MW/yr) would be required. This would equate to a market for SMES of 1-2 units per year of 400 MW/20 MWh assuming SMES can be cost competitive with batteries.

10.3 Transmission Market Segment

The current U.S. transmission system consists of about 150,000 miles of AC high voltage lines and about 2,500 miles of DC high voltage lines, supporting over 700,000 MW of generation capacity. The transmission system is typically characterized by lines of voltage capability from 38 kV up to 765 kV. As the demand for power increases over the next few decades there will be increased need for new transmission capacity. However, due to concerns about EMF, land use and other issues, new right-of-ways for transmission will become more difficult to obtain.

In addition, open access to transmission capacity and increased wheeling between regions is expected to put additional demands on the existing transmission capacity. It is for these reasons that there is a need to improve the load carrying capability and efficiency of existing transmission lines.

10.3.1 Transmission Market Trends

Year 2000. NERC has stated in their 1992 reliability assessment that one of the major challenges facing utilities in the near term will be ensuring adequate and reliable transmission systems in spite of increasing opposition to new transmission lines and increased use of transfers. The result of this opposition will be transmission systems which are increasingly loaded at or near reliability limits and are increasingly susceptible to system disturbances. Utilities will be relying more heavily on special protection systems and operating procedures to stretch the capability of their existing transmission systems.

This trend will help to create demand for technologies which will increase transfer capacity, enhance stability, and control flow in transmission lines. During the next 10 years, utilities will primarily focus on understanding these problems better and trying to determine which technologies will best meet their needs; major investment will most likely occur in later years. It is likely that by the year 2000 dynamic stability control will become an issue requiring attention.

Year 2030. Beyond the year 2000, issues such as siting new transmission lines and EMF are expected to become even more significant problems. Research is being conducted on the health effects of EMF. It is reasonable to assume that this will remain a very important issue for new transmission systems and upgrades of existing systems.

Open access to transmission systems for wholesale wheeling and the growth in NUGs will create ever more heavily loaded transmission systems. Potential growth in renewable sources of generation such as geothermal, solar, and wind, which may require long distance transmission, may also contribute to more heavily loaded transmission systems. Current concerns about reliability expressed by NERC may be reflected in actual reliability problems. Improving dynamic stability control may potentially emerge as an effective way to increase the transfer capacity of the existing transmission line system. The market for technologies which actively control reactive power by absorbing and delivering real power may develop out of this need.

10.3.2 SMES Transmission Market Penetration

Year 2000. A market for SMES (400-600 MW/400-600 MW-sec) in the year 2000 in transmission system applications will likely be primarily for demonstration projects. The specific capabilities of SMES in these applications will need to be demonstrated to utilities over the next 10 years. Demonstration projects would more precisely define the benefits of SMES as well as the technology's operational characteristics.

Year 2030. By the year 2030, it is anticipated that SMES will compete with battery energy storage systems, FACTS, and conventional reactive power control technologies for stability control of transmission lines. Presently, utilities spend approximately 5% of their transmission capital budget on conventional conditioning equipment. Based on previous Arthur D. Little work in evaluating the market for stability control technologies, these devices will be applied on an "as required" basis as systems become stressed. For this reason the demand for these technologies will not necessarily be tied to transmission system expansion or electricity demand growth. We would anticipate SMES to share the available market with both new and conventional conditioning equipment, obtaining a market of 5 to 10 units of 500 MW/500 MW-sec in size per year in this application.

10.4 Distribution Market Segment

The power distribution market segment is generally defined to include the lowest two voltage levels on the utility system down to the customer meter at the service entrance. The segment is comprised of distribution substations, primary distribution circuits, distribution transformers, and secondary distribution circuits which supply the majority of end-users of electrical energy. Some of the larger commercial and industrial end-users may be supplied directly from the transmission system. Primary distribution voltages usually range from 2400 volts to 34,500 volts (34.5 kV). In Exhibit 10-6, the distribution of customers is presented. It is important to note that although the sales of electricity are fairly equally distributed between industrial, commercial, and residential end-users, almost 88% of the number of customers are residential. As a result, the distribution infrastructure is much more extensive than the transmission infrastructure (there are over 1 million miles of distribution lines in the U.S.), although the capital investment per circuit mile is much lower. Thus the market for devices to service the distribution segment is characterized by a larger volume of relatively lower cost devices, relative to that found in the transmission segment. Due to the size of the distribution system, it is not surprising that it accounts for over 25% of the capital investment required by electric utilities (see Exhibit 10-2).

There are two major potential needs for storage units for distribution applications. The first is a technology which could be applied to solve the two-second-type power interruptions or power quality problems; this application would require relatively small amounts of energy storage. The characteristics of this device would typically be about 10-20 MW/50-100 MW-sec. A second application is focused on the long duration power quality problem or supplying local power supply; this application would require energy storage capacity measured in fractions of hours or greater, similar to an uninterruptable power supply (UPS).

10.4.1 Distribution Market Trends

Year 2000. The distribution market does not face the same external forces vis-a-vis siting associated with the transmission market. Siting of distribution lines and EMF are not major concerns in most areas. The most important focus is in providing reliable power to end-users. The major market drivers will be the expansion of

Exhibit 10-6 Distribution of Customers for Investor-Owned Utilities

service to new customers and the replacement and upgrade of existing distribution systems. An increase in the number of customers requiring (and willing to pay for) improved power quality may lead to an increase in the market for conventional technology for power quality.

Year 2030. Demand-side management (DSM) may provide the greatest long-term impacts on the need for power conditioning equipment at the distribution level. DSM and distribution automation have the potential for significant contributions to solving both capacity limitation problems and reliability problems.

The growth of the distribution system over the long term and how that is managed will also have significant implications in this market. A trend toward increased networking, for instance, could help to increase reliability for customers without the need for new power conditioning equipment. Radial expansion of systems, on the other hand, might increase the potential needs for power conditioning in the distribution system.

10.4.2 SMES Distribution Market Penetration

Year 2000. The need for technologies to solve power quality problems such as short interruptions or voltage sag will most likely be dealt with on a customer-by-customer basis over this time period. Based on the current costs of SMES technology, it

appears that this will not be the most cost-effective manner for handling this problem. Therefore, it does not appear there will be a market for this technology within the distribution market during this timeframe.

Year 2030. SMES does not appear to offer attractive economics for applications requiring longer duration storage in small sizes. Therefore, a market does not seem to exist for distributed diurnal storage applications of SMES.

As was true in the near-term time frame, it will be difficult for SMES to compete in the market for solving power quality problems at the distribution level over the long term due to the relatively low cost of conventional power conditioning equipment. Applications targeted at specific large commercial and industrial end-users either on the utility side or the customer side of the meter seem to be the best long-term application. This need has been addressed in the customer service market segment.

10.5 Customer Service Market Segment

The customer service equipment market lies primarily with the end-user. The power conditioning market is extremely broad in terms of the problems and types of equipment being applied today. Our analysis has focussed on equipment which addresses the voltage "ride-through" problems associated with sensitive equipment within large commercial and industrial manufacturing facilities. Ride-through requirements for this narrowly defined market segment would be a minimum of 2 seconds with a 1 to 5 MVA capacity. Since approximately 65% of utility sales are to the commercial and industrial sector; (Exhibit 10-6) it is reasonable to assume that significant attention may be focused on these problems in the future.

10.5.1 Customer Service Market Trends

Year 2000. During the next decade, the majority of customer service problems are expected to fall under two general categories; improving power quality and energy utilization. The value of these problems is related to the cost of an interruption which includes costs associated with manufacturing process or production line losses and productivity losses within commercial businesses. Estimates vary widely regarding the cost of these losses to the manufacturing sector. Estimates as high as \$15-30 billion per year (1992 \$) have been developed based on assumptions of 1½ to 3 cents of every sales dollar being spent on power quality related problems by industrial customers.^[145] Within the commercial sector, estimates as high as \$15 billion per year have been suggested.^[146]

Currently, the market for devices to solve power quality problems is filled by on-line uninterruptible power supplies (UPS). Market forecasts for on-line UPS systems^[186] indicate that approximately 12.5% of the shipments of UPS devices of 500 kVA and greater are for industrial end-users. It is within this market segment that the greatest need for voltage sag protection or a 2 second ride through capability exists. As end-users realize the potential value of devices which reduce their interruption-related costs, a market for this application will develop. Initially, the market will be in

industries where power interruptions have the greatest cost impact. Based on the current market forecast, there will be approximately \$110 million in cumulative sales over the next ten years in this market, the majority of which will be for on-line UPS systems.

Year 2030. Over the longer term, there is increased potential for technologies which will address the need for end-use load leveling. Advanced batteries and flywheels are likely to be attractive technologies for this application due to low production costs from carry-over manufacturing economies of scale associated with their adoption in other high volume markets such as electric vehicles. These technologies will also be able to address the 2 second voltage sag problem. Emphasis is increasingly being placed on end-use equipment robustness which over this longer term is expected to essentially eliminate the need to address the 2 second voltage sag problem.

10.5.2 SMES Customer Service Market Penetration

Year 2000. Significant potential exists for SMES in the 1-2 MW/1-2 MW-sec size range to be applied to address voltage sag related problems in industries that place a high value on avoiding power related process interruptions. This may apply to batch process industries such as electronics and pharmaceuticals and production line industries such as automobile manufacturers.

Based on the market forecast for UPS devices of 500 kVA and greater^[186] of \$110 million of cumulative sales over the next ten years, and a cost of these power quality devices of \$500/kVA, there would be a need for 220,000 kVA over ten years, or approximately 22 MVA per year. This equates to a potential market of up to 22, 1 MVA units per year. Because this market is currently being filled by on-line UPS systems, it may be several years before this market is shared by SMES and later by technologies such as batteries and flywheels. On-line UPS systems typically sell for \$300/kVA. Starting prices for SMES devices in this size range are approximately \$500-1000/kVA which will limit their initial market penetration.

The actual market penetration by SMES will be limited due to acceptance in the early years and high initial cost. Niche market opportunities where the compact nature and portability of early SMES devices can be best exploited will most likely provide the initial market. By the year 2000 it is expected that competing technologies will emerge offering equivalent technical specifications and more attractive economics. This will limit the market potential for SMES devices to approximately 3-7 units of 1-2 MW/1-2 MW-sec per year over this time period.

Year 2030. The competition from technologies which may more cost effectively offer load leveling storage capability in addition to protection from short duration interruptions will decrease the market share of SMES in this application over time. High energy storage and operating costs will make it difficult for SMES to compete with technologies such as batteries and potentially flywheels, which by the year 2030, should be mature technologies. The long-term market for SMES as well as

competing technologies in this application may also be substantially reduced by improvements in the ride-through capabilities of equipment used in critical processes and services. By the year 2030, we expect SMES to have a negligible market share in customer end-use applications.

11.0 SMES Technical Issues

11.1 System Efficiency

The system efficiency of SMES systems is driven by two primary components, the refrigeration plant requirement for maintaining the superconductive coil at cryogenic temperatures, and the energy loss associated with the round-trip efficiency of the power conditioning system (PCS). Of these two components, the refrigeration losses are the larger of the two for systems smaller than 100 MWh of storage capacity, whereas PCS losses dominate for very large (>100 MWh) systems.

A few attempts have been made to try to quantify the refrigeration losses for various coil sizes.^[85] For the small systems a substantial component of the losses are associated with the current leads between the cold and warm part of the system. For larger systems (>100 MWh) this component becomes very small. The other major component is associated with conduction. Some of these losses may be reduced by design improvements and increased insulation use. There is limited data available on refrigeration loads based on a few small superconducting magnet systems which have been built or are being designed for upcoming experimental projects. This information has been provided by the National High Magnetic Field Laboratory in Tallahassee, Florida.^[101] A limited amount of data for larger systems is available in the literature, but the general trend can be developed. Exhibit 11-1 indicates the range of losses based on the available data and discussions with several individuals regarding how the losses may be reduced in the future.^[174.4, 174.5 174.6, 174.7] Refrigeration loads are expected to be approximately 10-20% of the total stored energy for systems of 10-20 MWh in the optimized designs. For systems smaller than 1 MWh the daily refrigeration load rapidly exceeds 100% of the stored energy.

Exhibit 11-1 SMES Daily Refrigeration Energy Requirements as a Percentage of Stored Energy

Toroidal system designs are expected to have approximately two to four times the refrigeration load of solenoid designs due to the increased mass of these systems.

Based on the data shown in Exhibit 11-1 and that provided by a micro-SMES equipment supplier, cost ranges for refrigeration energy for different sizes of storage units can be developed as shown in Exhibit 11-2.

Exhibit 11-2 SMES - Annual Costs for Refrigeration Energy

Stored Energy Capability MWh	Refrigeration Energy Range MWh/day	Annual Cost Refrigeration Energy \$/yr ⁽¹⁾
.0001 - .0006	1.2 - 2.0	30,000 - 54,000
0.1	0.5 - 1.8	12,000 - 45,000
1.0	0.4 - 1.2	10,000 - 30,000
10.0	1.0 - 3.0	25,000 - 74,000
100.0	4.0 - 12.0	100,000 - 300,000

(1) Assuming 6.8¢/kWh average price of electricity in 1992 \$ (Exh. 4-8)

The round-trip efficiency of SMES devices of 1 MW or larger is expected to be approximately 93-95% and may approach 97% over the long term. PCS systems and inverter technology are sufficiently well understood to determine these losses with a fairly high degree of accuracy. Toroid and solenoid designs will have PCS losses of the same magnitude.

11.2 Electro-Magnetic Field (EMF) Concerns

There has recently been a significant amount of public and media attention focussed on the possible adverse health effects of electro-magnetic fields (EMF) associated with high voltage transmission lines^[151,152,153]. Most of the research effort has been directed at determining if a statistical association exists between human EMF exposure and various forms of cancer. To-date there has been no conclusive evidence suggesting that a significant correlation does or does not exist between increased exposure and the risk of cancer. Recent studies performed in Sweden have suggested that there is a link between increased evidence of childhood leukemia and exposure to fields produced by high voltage transmission lines.^[149,150] There are currently several studies being proposed in the U.S. to research the effects of EMF associated with high voltage transmission lines (DOE, EPA, EPRI and Calif. Dept. of Health Services)^[154].

What is significant is the current level of public concern and the effect this is having on the ability of utilities to upgrade and site new transmission lines. Moratoriums on new transmission lines over 60 kV are being discussed in at least two states (Rhode

Island and Wisconsin). Major opposition is facing new power lines in Florida, Kansas, Michigan, Wisconsin, Rhode Island and others.^[154]

SMES systems store their energy in an extensive static magnetic energy field (DC) which is generated by the circulating current. SMES coils charge and discharge at a frequency which is much slower than the frequency of power lines or household wiring where the alternating current creates a 60 Hz, time varying magnetic field. Exposure to 60 Hz wiring creates complicated electromagnetic environments. Maxwell's current equations indicate there is a distinct difference between the effects of time varying 60 Hz (AC) and static (DC) fields. Time varying fields (AC) induce currents within conducting loops in an object whereas static fields can only act on existing current loops. This is a major difference between AC and DC fields. Examples of conducting loops within humans are the circulatory and nervous systems.

Fields of 5 Tesla (50,000 Gauss) or less are thought by some to be below the point where significant health risks such as blood pressure increases or nerve conduction velocity impacts may be created.^[156] It is important to understand, however, that there is a significant lack of information and knowledge regarding the effects of DC fields as there has only been very limited practical experience. Fields of 5 Tesla are expected to be the strength which would be present in the immediate vicinity of a large, utility size SMES systems.^[156] According to the developers of large SMES systems a 5 Tesla magnetic field will be seen inside the SMES vacuum containment, which is inaccessible for SMES plant personnel. Plant personnel will be excluded from coil areas exceeding 200 Gauss, and all general public will be excluded from fields larger than 10 Gauss in current SMES plans. Fields of 0.5 to 2.0 Tesla are used in magnetic-resonance-imaging (MRI). Most patients report no sensation associated with a 10 minute stay in the field. To put this in perspective, the strength of the earth's fields reach a maximum of .05-.07 Gauss ($5-7 \times 10^{-5}$ Tesla) at the poles.

There are currently no established government regulations on continuous exposure to DC magnetic fields or AC fields for that matter. Various institutions have established guidelines for exposure to DC or AC magnetic fields. The U.S. Department of Energy restricts the maximum field exposure over an eight hour period to 100 gauss.^[156] Magnetic fields over 10 gauss have been found to have possible effects on the operation of pacemakers and this has been used as a guide for setting exposure limits around DC fields, although it does not appear that any formal guidelines exists.^[155]

If the 10 gauss level is chosen as the maximum level of EMF that a person should be exposed to, the space requirements for the larger SMES systems (>10 MWh) become quite large. Exhibit 11-3 is a comparison of the distance to the 10 gauss level and the SMES storage capacity^[5,10,130,156]. Shielding can be added to decrease this distance, however, this may add considerable expense for the larger systems. Possible effects of magnetic fields on animals and birds have been raised. Some limited studies have been performed regarding the influence of magnetic fields on the

Exhibit 11-3 Approximate Range of Distance from Center of Coil to 10 Gauss Level for Unshielded Solenoid SMES Systems

homing ability of pigeons. Monarch butterflies and honeybees have been studied for magnetic field effects, but it appears that the data is insufficient to draw conclusions from. Studies of rodents have indicated that they may avoid areas of high magnetic fields, but the data is somewhat limited.

Toroid designs have the advantage of having very low EMF, but require more material and have been estimated to be 2-4 times more expensive in cost. This extra cost may be justified in some of the smaller applications where space restrictions apply. It may also be less of a factor for systems which have relatively small amounts of storage capacity (<0.5 MWh).

In summary, the evaluation of the effect of DC magnetic fields on humans, animals, birds and other living organisms is hampered by a lack of sufficient data required to characterize the phenomenon. Work ongoing on the effect of low frequency, AC (60 Hz) magnetic fields is based on the data collected in the proximity of power lines. There are hundreds of thousands of miles of high voltage power lines available from which this information may be derived and correlations are still difficult to develop. Significant amounts of time will be required to determine true causal relationships. Evaluation of the effects of DC exposure will be limited by a lack of historical data.

In any case a significant development of SMES with many large applications is likely to require sufficient evidence regarding the safety of DC magnetic fields in order to satisfy public uncertainty and potential opposition.

Glossary of Terms

AC - Alternating current

AFUDC - Allowance for Funds Used During Construction; interest on funds expended during the construction phase of a project.

Black start capability - The ability of a generating unit to start power generation without external power supplies.

Bulk Storage - Storage of energy in large quantities, usually implying tens or hundreds of MWhs for economic benefits of using low cost off-peak power.

Capacity factor - Total energy output over a period of time divided by the output if operated at 100% capacity for 100% of the period.

Capacity margins - The fraction of generating capacity available to provide for scheduled maintenance, emergency outages, system operating requirements, and unforeseen electricity demand.

Cold - supported SMES - a SMES device where the magnetic forces exerted by the coil are contained by a steel structural system.

Cycling capability - The ability of a generating unit to handle on/off, two shift operations, and up/down variations in unit loading.

DC - Direct current

Dispatchability - The ability of a generating unit to increase or decrease generation, or to be brought on line or shut down, at the request of the utility's system operator.

Dispatching - Operating control of an integrated electric system including assigning generator levels and controlling transmission and distribution circuits.

Distribution - The electric utility delivery system between the transmission level and the end user. Typical distribution line voltages are 2500 V to 34.5 kV.

Diurnal storage - Energy storage capacity used on a daily basis, typically at off-peak or night-time hours for peak or daytime use. Usually performed for economic benefits of using low cost off-peak power.

Glossary of Terms (continued)

Dynamic stability - The interactions of generating sources that undergo slow or gradual changes in operating conditions. Dynamic stability on power systems is made possible by the action of automatic voltage regulators capable of increasing or decreasing flux within a synchronous machine thereby creating restoring forces equal to or greater than the disturbing forces.

Earth - supported SMES - a SMES device where the magnetic forces exerted by the coil are contained by a system requiring integral ground support - e.g. a reinforced concrete trench.

EMF - Electro-magnetic field - The magnetic field produced by a current flowing through a conductor or inductor.

Environmental externalities - a value placed on environmental emissions (e.g. from a generation resource) and explicitly included in relevant economic analysis.

FACTS - Flexible AC transmission system technology is based on the use of high speed power electronic controllers typically in the form of fault-tolerant micro-processor based computers and high power switching semiconductors. The advanced devices can supply and absorb both real and reactive power of controlled amplitude.

Frequency - As applied to electrical power systems, the number of alternating current or voltage cycles per second as measured in Hertz.

Generation - The production of electrical energy from primary fuel source - e.g. gas, oil, hydro, solar.

Hertz - (Hz) - a standard unit of frequency equivalent to cycles per second.

Interruption - The complete loss of voltage on one or more phase conductors.

Life-cycle analysis - A method of accounting for all of the costs associated with a project during its full life.

Loopflow - Where substantial quantities of power flow on neighboring utility transmission systems or when a transmission system is not interconnected and a "loop" exists with current typically flowing in a circular pattern.

MJ - Megajoule; 1×10^6 Joules or 1×10^6 Watt-seconds

MW - Megawatt; 1×10^6 Watts

MWh - Megawatt hour; 1×10^6 Watt-hours

MWs - Megawatt second; 1×10^6 Watt-seconds

Glossary of Terms (continued)

NERC - North American Electric Reliability Council - Nine Regional Councils and one Affiliate that together encompass virtually all of the electric utility systems in the United States, Canada, and the northern portion of Baja California, Mexico. Formed in 1968, its purpose is to coordinate, promote, and communicate about the reliability of generation and transmission systems.

NUG - Non-Utility Generator - An electric generating facility connected to a utility system which is less than 50% owned by a public utility. This includes Qualifying Facilities, Independent Power Producers, and Exempt Wholesale Generators.

Power factor - The cosine of the angle by which the voltage leads the current waveforms.

Ramping capability - The ability of a generating unit to follow instantaneous changes in load.

Reactive power - The product of the voltage and current components which either lag (-90°) or lead ($+90^\circ$) electrical degrees.

Real power - The product of the rms (root mean square) voltage, rms current and power factor.

Reserve margin - Generation reserves which are available to meet unexpected system load increases or equipment failures. Usually divided into two parts; primary reserves and secondary reserves

Reserves, primary - Generating capacity which is able to respond rapidly (usually less than ten minutes) to instantaneous emergencies such as unit tripping or loss of imported power, either spinning (synchronized to the system) or able to quick start (non-synchronized).

Reserves, secondary - Generating capacity with a loading requirement of approximately 30 minutes in order to respond to less severe impacts such as load forecasting error.

Revenue requirements - the amount of money that must be collected by a utility from customers to compensate for all charges for capital, goods, and services associated with an investment.

SMES - Superconducting Magnetic Energy Storage

Solenoid design - A coil design for a SMES device where the coils are wrapped around the axis of a cylinder.

Glossary of Terms (continued)

Superconductor - Materials which exhibit the phenomenon of zero electrical resistance at temperatures approaching absolute zero. A superconducting circuit maintains constant the value of the total flux enclosed by the circuit at the time it entered the superconducting state.

Thermal limit - The maximum current handling capacity of an electrical conductor based on its maximum allowable temperature rating.

Toroidal design - A coil design for a SMES device where the coils are wrapped around the axis of a cylinder and the cylinder is then formed into a circle (a torous).

Transfer capacity - The current handling capacity of a transmission line which meets an established set of system reliability and stability criteria.

Transient stability - The amount of power that can be transmitted with stability following a major disturbance such as a transmission systems faults, sudden load changes, loss of generating units or line switching.

Transients - A unidirectional voltage or current impulse of either polarity or a damped oscillatory wave with the first peak occurring in either polarity.

Transmission - The electric utility delivery system between generation and distribution. Typical transmission line voltage levels are between 34.5 kV and 765kV. Sometimes a separate sub-transmission category is defined between 34.5 kV and 115 kV.

Voltage Sag - A sudden reduction of the voltage in an electrical system lasting from one-half cycle to a few seconds.

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