

# 12

## SUPERCONDUCTING MAGNETIC ENERGY STORAGE

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### Introduction

Superconducting Magnetic Energy Storage (SMES) exploits advances in materials and power electronics technologies to achieve a novel means of energy storage based on three principles of physics:

- Some materials (superconductors) carry current with no resistive losses.
- Electric currents induce magnetic fields.
- Magnetic fields are a form of energy that can be stored.

The combination of these fundamental principles provides the potential for the highly efficient storage of electrical energy in a superconducting coil. Operationally, SMES is different from other storage technologies in that a continuously circulating current within the superconducting coil produces the stored energy. In addition, the only conversion process in the SMES system is from AC to DC power conversion, i.e., there are none of the thermodynamic losses inherent in the conversion of chemical (battery) and mechanical (flywheel) energy storage to electricity.

SMES was originally proposed [1,2] for large-scale, load leveling, but, because of its rapid discharge capabilities, it has been implemented on electric power systems for pulsed-power and system-stability applications.<sup>18</sup> Figure 12-1 is a picture of the only SMES unit commercially offered at present (American Superconductor's D-SMES). This chapter primarily emphasizes existing SMES applications, but also describes some of the extensive design and development programs for large-scale SMES plants that were conducted in the recent past. Figure 12-2 shows such a plant that is rated at 500 MW<sub>ac</sub> [3] and stores sufficient energy to deliver this power for 6 to 8 hours. The coil shown is about 1000 meters in diameter and is located at sufficient depth below grade for the surrounding soil to support the magnetic loads from the coil.

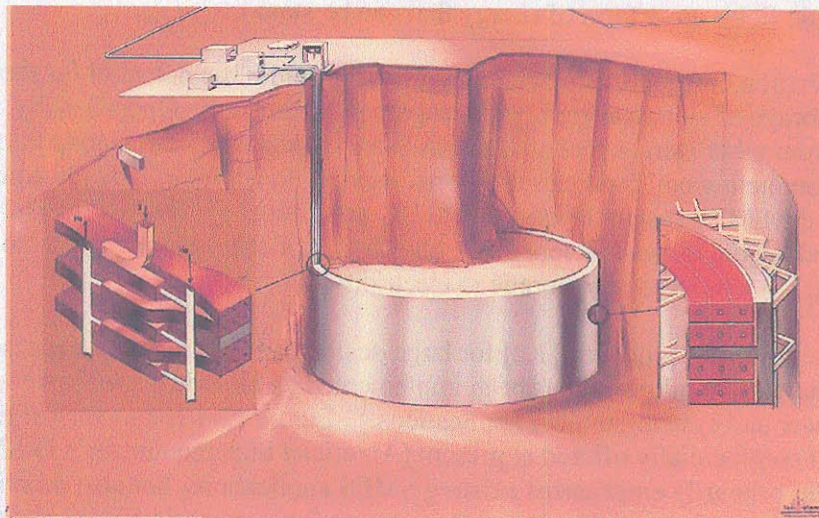
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<sup>18</sup> A bibliography listing major reports relevant SMES development is included at the end of this chapter.





**Figure 12-1**  
**A Trailer Mounted D-SMES Unit With 3MW and Up to 16 MVA Capacities**  
(Picture Supplied by American Superconductor)



**Figure 12-2**  
**Artist Concept of a Large-Scale Diurnal SMES System Constructed Underground**

## Description

### System Components

The power and stored energy in a SMES system are determined by application and site-specific requirements. Once these values are set, a system can be designed with adequate margin to provide the required energy on demand. As illustrated by the SMES systems



shown and, SMES units have been proposed over a wide range of power (1 to 1000 MW<sub>ac</sub>) and energy storage ratings (0.3 kWh to 1000 MWh). Independent of size, all SMES systems include a superconducting coil, a refrigerator, a power conversion system (PCS), and a control system as shown in Figure 12-3. Each of these components is discussed in this section.

### The Coil and The Superconductor

The superconducting coil, the heart of the SMES system, stores energy in the magnetic field generated by a circulating current. Since the coil is an inductor, the stored energy is proportional to the square of the current, as described by the familiar equation:

$$E = \frac{1}{2}LI^2, \quad \text{Eq. 12-1}$$

Where L is the inductance of the coil, I is the current, and E is the stored energy.

The total stored energy, or the level of charge, can be found from the above equation and the current in the coil. The maximum practical stored energy, however, is determined by two factors.

- The size and geometry of the coil, which determine the inductance.

The characteristics of the conductor, which determine the maximum current.

Superconductors carry substantial currents in high magnetic fields. For example, at 5 Tesla, which is 100,000 times greater than the earth's field, practical superconductors can carry currents of 300,000 A/cm<sup>2</sup>.

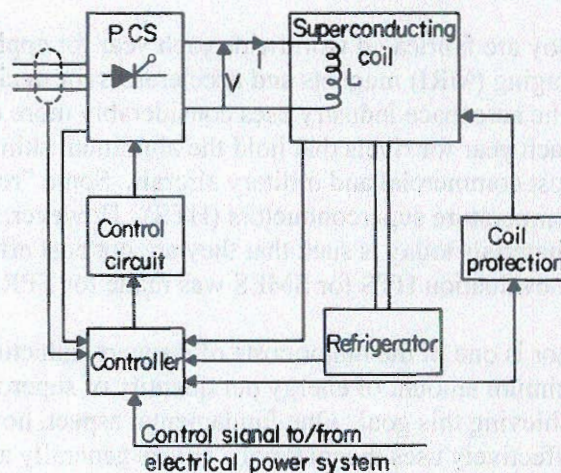
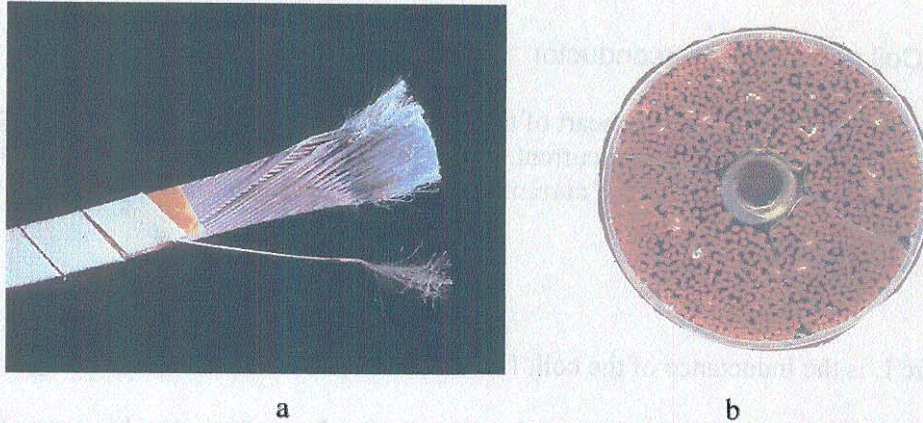


Figure 12-3  
Simplified Block Diagram of a SMES System Showing Major Components



All practical SMES systems installed to date use a superconducting alloy of niobium and titanium (Nb-Ti), which requires operation at temperatures near the boiling point of liquid helium, about 4.2 K (-269C or -452°F) which is 4.2 degrees centigrade above absolute zero. Typical conductors made of this material are shown in Figure 12-4.



**Figure 12-4**  
**Typical Conductors Made of the Superconductor Nb-Ti (LBNL & LLNL)**

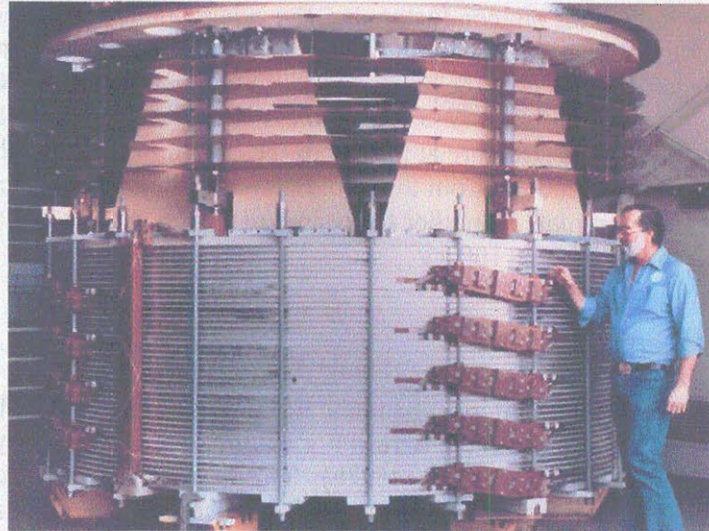
Figure 12-4a, on the left, is a flattened cable made of 30 composite strands wrapped in an insulator made of Kapton and epoxy-fiberglass. Each strand is 0.7 mm in diameter and contains several thousand, 6  $\mu\text{m}$  diameter Nb-Ti filaments extruded in a copper matrix. Figure 12-4b, on the right, is a CICC cable made of several hundred of these strands in a stainless steel conduit. During operation, helium is in direct contact with the superconducting strands and, in the CICC shown, the helium flows through the central tube. Lawrence Berkeley National Lab (LBNL) and Lawrence Livermore National Lab (LLNL) supplied figures 4a and 4b, respectively.

Many tons of Nb-Ti alloy are fabricated worldwide each year for applications such as magnetic resonance imaging (MRI) magnets and accelerators for nuclear physics research. In addition, the aerospace industry uses considerably more of a slightly different Nb-Ti alloy each year for rivets that hold the aluminum skin in place on the bodies and wings of most commercial and military aircraft. Some "research grade" SMES coils use high-temperature superconductors (HTS). However, the state of development of these materials today is such that they are not cost effective for utility-application SMES. An evaluation HTS for SMES was made for EPRI in 1998 [4].

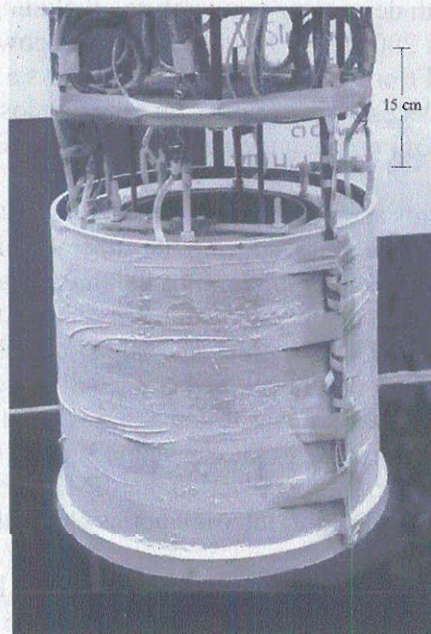
Since the superconductor is one of the major costs of a superconducting coil, one design goal is to store the maximum amount of energy per quantity of superconductor. Many factors contribute to achieving this goal. One fundamental aspect, however, is to select a coil design that most effectively uses the material. This is generally accomplished by a solenoidal configuration, as in the two SMES installations shown in Figure 12-5 and Figure 12-6. Figure 12-5 shows the 30 MJ [5] superconducting coil developed by the Los



Alamos National Laboratory (LANL) and installed by the Bonneville Power Administration at the Tacoma substation. Figure 12-6 is a small, 1 MJ SMES coil.



**Figure 12-5**  
**30 MJ Superconducting Coil Developed by the Los Alamos National Laboratory (LANL)**



**Figure 12-6**  
**1 MJ SMES Coil in a Liquid Helium Vessel (LANL)**



Since only a few SMES coils have been constructed and installed, there is little experience with a generic design. This is true even for the small or micro-SMES units for power-quality applications, where several different coil designs have been used.

A primary consideration in the design of a SMES coil is the maximum allowable current in the conductor. It depends on: conductor size, the superconducting materials used, the resulting magnetic field, and the operating temperature. The magnetic forces can be significant in large coils and must be reacted by a containment structure within or around the coil. The coil shown in Figure 12-5 has stainless straps within the cabled conductor for this purpose. The baffle structure at the top of the coil limits gas circulation and maintains a temperature gradient from the liquid helium bath around the coil to the ambient-temperature top plate. Another factor in coil design is the withstand voltage, which can range from 10 kV to 100 kV.

### Cryogenic Refrigerator

The superconducting SMES coil must be maintained at a temperature sufficiently low to sustain a superconducting state in the wires. For commercial SMES today, this temperature is about 4.5 K (-269°C, or -452°F). This thermal operating regime is maintained by a special cryogenic refrigerator [6] that uses helium as the refrigerant. Helium must be used as the so-called "working fluid" in such a refrigerator because it is the only material that is not a solid at these temperatures. Just as a conventional refrigerator requires power to operate, electricity is used to power the cryogenic refrigerator. Thermodynamic analyses have shown that power required to remove heat from the coil increases with decreasing temperature. Including inefficiencies within the refrigerator itself, between 200 and 1000 watts of electric power are required for each watt that must be removed from the 4.5 K environment. As a result, design of SMES and other cryogenic systems places a high priority on reducing losses within the superconducting coils and minimizing the flow of heat into the cold environment.

Both the power requirements and the physical dimensions of the refrigerator depend on the amount of heat that must be removed from the superconducting coil. The refrigerator consists of one or more compressors for gaseous helium and a vacuum enclosure called a "cold-box", which receives the compressed, ambient-temperature helium gas and produces liquid helium for cooling the coil. The 30 MJ coil shown in Figure 12-5 required a dedicated refrigerator that occupied two small trailers, one for the compressor and one for the "cold box". The coil was tested at 4.5 K and then removed from the cryostat while still cold, which leads to the ice on the surface of the helium vessel. The coil is approximately the size of early power quality SMES coils, such as those fabricated by American Superconductor Inc. and Intermagnetics General Corporation.

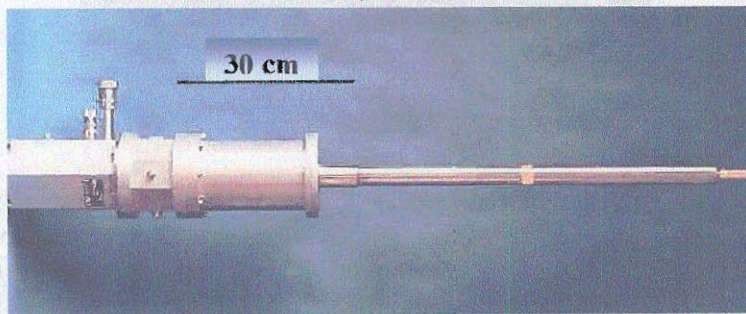
Small SMES coils and modern MRI magnets are designed to have such low losses that very small refrigerators are adequate. Figure 12-7 and Figure 12-8 show cryogenic refrigerators of different capacities. In Figure 12-7, a small cryogenic refrigerator (the 30 cm section) and a cold-finger extension that would be appropriate for recondensing liquid



helium to cool a superconducting coil are shown. This refrigerator can remove about 5 W at 4.5 K, which is the heat load that might be expected in a micro-SMES for power-quality applications. Such refrigerators usually operate with the cold finger pointing downward but other orientations are possible. Figure 12-8 shows a large liquid helium refrigerator at the Japanese Atomic Energy Research Institute (JAERI). Such a refrigerator would be appropriate for the diurnal SMES installation shown in. It can remove about 10 kW of heat from a large magnet operating at 4.5 K.

### Power Conversion System

Charging and discharging a SMES coil is different from that of other storage technologies. The coil carries a current at any state of charge. Since the current always flows in one direction, the power conversion system (PCS) must produce a positive voltage across the coil when energy is to be stored, which causes the current to increase. Similarly, for discharge, the electronics in the PCS are adjusted to make it appear as a load across the coil. This produces a negative voltage causing the coil to discharge. The product of this applied voltage and the instantaneous current determines the power.



**Figure 12-7**  
**Small Cryogenic Refrigerator and Cold-Finger Extension (Cryomech Inc.)**





**Figure 12-8**  
**Large Liquid Helium Refrigerator (JAERI)**

SMES manufacturers design their systems so that both the coil current and the allowable voltage include safety and performance margins. Thus, the PCS power capacity typically determines the rated capacity of the SMES unit. In particular, as energy is removed from the coil, the current decreases. As a result, the PCS must be designed to deliver rated power at the lowest operational coil current, which is about half of the maximum current. Equivalently, about a quarter of the stored energy remains in the coil at the end of a typical discharge.

The PCS provides an interface between the stored energy (related to the direct current in the coil) and the AC power grid. Several different designs have been suggested for the PCS, depending on the application and the design of the SMES coil. The power that can be delivered by the SMES plant depends on the charge status (the current  $I$ ) and the voltage capability of the PCS, which must be compatible with the grid.

### Control System

The control system establishes a link between power demands from the grid and power flow to and from the SMES coil. It receives dispatch signals from the power grid and status information from the SMES coil. The integration of the dispatch request and charge level determines the response of the SMES unit. The control system also measures the condition of the SMES coil, the refrigerator, and other equipment. It



maintains system safety and sends system status information to the operator. SMES systems provide remote observation and control via internet connections.

### **Technology Attributes**

#### **Power Rating**

The power of a SMES system is established to meet the requirements of the application, e.g., power quality or power system stability. In general, the maximum power is the smaller of two quantities the PCS power rating and the product of the peak coil current and the maximum coil withstand voltage.

The power rating of commercial micro-SMES installations range from 1 to 3 MW<sub>ac</sub> as discussed in the next section. A much larger unit is now being installed by the Center for Advanced Power Systems (CAPS) at the National High Magnetic Field Laboratory (NHMFL) in Tallahassee, Florida. The PCS for this coil will initially have an installed capacity of 5 MW with planned future enhancement to 25 MW<sub>ac</sub>. The superconducting coil, however, was designed to deliver 100 MW<sub>dc</sub>, i.e., the product of the design current and design voltage is 100 MW<sub>dc</sub>.

#### **Energy Storage Rating**

The micro-SMES plants listed above deliver 3 to 6 MJ (0.8 to 1.6 kWh, roughly equivalent to the capacity of a 12 volt, 100 Ah lead acid battery). Because the power rating of these units is so high, this entire quantity of energy can be delivered (i.e., the coil can be fully discharged) in a second or so. The larger, 100 MW<sub>dc</sub> coil to be installed at NHMFL, mentioned above, was originally designed for a one-second discharge in conjunction with the unified power flow controller (UPFC) operated by American Electric Power (AEP) at its Inez Substation. This coil thus stores about 100 MJ (28 kWh). When the converter at NHMFL is upgraded to 25 MW<sub>ac</sub>, the coil will be discharged in about 4 seconds.

#### **Physical Dimensions of the SMES Installation**

The physical size of a SMES system is the combined sizes of the coil, the refrigerator and the PCS. Each of these depends on a variety of factors. The coil mounted in a cryostat is often one of the smaller elements. A 3 MJ micro-SMES system (coil, PCS, refrigerator and all auxiliary equipment) is completely contained in a 40-ft trailer.

#### **Efficiency**

The overall efficiency of a SMES plant depends on many factors. In principle, it can be as high as 95 % in very large systems. For small power quality systems, on the other



hand, the overall system efficiency is less. Fortunately, in these applications, efficiency is usually not a significant economic driver. The SMES coil stores energy with absolutely no loss while the current is constant. There are, however, some losses associated with changing current during charging and discharging, and the resulting change in magnetic field. In general, these losses, which are referred to as eddy current and hysteresis losses, are also small.

Unfortunately, other parts of the SMES system may not be as efficient as the coil itself. In particular, there are two potentially significant, continuous energy losses, which are application specific:

- The first is associated with the way SMES systems store the energy. The current in the coil must be flow continuously, and it circulates through the PCS. Both the interconnecting conductors and the silicon-based components of the PCS are resistive. Thus, there are continuous resistive losses in the PCS. This is different from batteries, for example, where there is current in the PCS only during charge and discharge.
- The second is the energy that is needed to operate the refrigerator that removes the heat that flows to the coil from room temperature via: a) conduction along the mechanical supports, b) radiation through the vacuum containment vessel, and c) along the current leads that extend from ambient temperature to the coil operating temperature.

The overall efficiency of a SMES plant depends on many factors. Diurnal (load-leveling) SMES plants designed 20 years ago were estimated to have efficiencies of 90 to 92%. Power quality and system stability applications do not require high efficiency because the cost of maintenance power is much less than the potential losses to the user due to a power outage. Developers rarely quote efficiencies for such systems, although refrigeration requirements are usually specified. A 3 MJ/3 MW<sub>ac</sub> micro-SMES system, for example, requires about 13 kW of continuous refrigeration power.

## **Status of SMES Deployment**

### **D-SMES**

Today the only commercial SMES product is the D-SMES unit produced by American Superconductor. The individual, trailer-mounted D-SMES units consist of a magnet that contains 3 MJ of stored energy (see Figure 12-1). They can deliver 3 MW for about 1 second and 8 MVAR continuously at 480 V<sub>ac</sub>. This is accomplished by a PCS that has full 4-quadrant control and uses IGBT based inverters. There is an instantaneous overload capability of 2.3 times continuous (2.3x) for reactive power in the inverter so that the dynamic reactive output can be as high as 18.4 MVAR for up to 1 second. Three networked systems with a total of 9 units have been installed, as indicated in Table 12-1. An additional unit has been ordered.



**Table 12-1**  
**Installed D-SMES Units**

Start of Operation	Host	Location	Application
June 2000	Wisconsin Public Service	Northern Wisconsin	Transmission Loop Voltage Stability - 6 Units, installed at distributed locations
July 2000	Alliant Energy	Reedsburg, Wisconsin	Transmission Voltage Stability
May 2002	Entergy	North Texas	Voltage Stability - 2 Units

### **Micro-SMES**

Prior to the development of the D-SMES concept, American Superconductor supplied several small power quality SMES units, which are still operational. Designated "Micro"-SMES, these units have been installed around the world in mostly industrial settings to control voltage sag problems on the electrical grid. These are listed in Table 12-2..

### **SMES Test and Evaluations**

In 1992, the Defense Advanced Research Projects Agency (DARPA) issued a request for proposals to build an intermediate sized SMES system for a utility application. There was some consideration/discussion of dual use [7] with a military pulsed power application. As finally released, there was no requirement for a military application as part of the design. A contract was awarded to Babcock and Wilcox (B&W) to build and then install a 0.5 MWh, 20 MW<sub>ac</sub> plant in Anchorage, Alaska. However, a variety of factors resulted in several changes in direction of the program. It eventually evolved into a program for BWX Technologies to build a 100 MJ (0.028 MWh) coil for the National High Magnetic Field Laboratory (NHMFL) in Tallahassee, Florida. This coil is expected to be completed in 2003 and will be installed at the Center for Advanced Power Systems (CAPS), a part of NHMFL and Florida State University. The coil will be initially operated with a 5 MW<sub>ac</sub> converter, which is appropriate for the local power system. It is designed, however, to accommodate power flows of up to 100 MW<sub>ac</sub>.



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**Table 12-2  
Existing Installations of Micro-SMES**

Start of Operation	Customer	Location	Application	Power (Voltage)	Energy, MJ
May 1992	Central Hudson G&E	Fishkill, NY	Semiconductor Testing Facility	500 kVA (480 V <sub>ac</sub> )	1.0
December 1993	Tyndall AFB	Panama City, FL	Five General Military Buildings	500 kVA (480 V <sub>ac</sub> )	1.0
March 1993	CYANCO	Winnemucca, NV	400 HP/4160V Motor at Chemical Plant	500 kVA (4160 V <sub>ac</sub> )	1.0(+)
May 1995	Brookhaven National Laboratory	Upton, NY	Light Source Research Center Ultra-violet Light source, ring, and experiment station	1.4 MVA (480 V <sub>ac</sub> )	2.8
May 1995	McClellan AFB	Sacramento, CA	Semiconductor Chip Mfg. Lab Fiber Optic Mfg. Facility Removed when Base Closed	750 kVA (480 V <sub>ac</sub> )	2.8
July 1996	U.S. Air Force	Tinker AFB, OK	DC Link Support for two 800 kW/1000kVA Ups	1.0 MVA (560 V <sub>ac</sub> )	2.8
June 1997	U.S. Air Force	Tinker AFB, OK	DC Link Support for two 800 kW/1000kVA UPS	1.0 MVA (560 V <sub>ac</sub> )	2.8
April 1997	SAPPI - Stanger	Stanger, South Africa	1000 kVA Paper Machine	1.0 MVA (400 V <sub>ac</sub> )	3.0
May 1997	AmeriMark Plastics	Fairbluff, NC	Plastic Extrusion Plant Removed when plant sold	1.4 MVA (480 V <sub>ac</sub> )	3.0
May 1999	STEWEAG	Gleisdorf, Austria	Automotive Parts Foundry	1.4 MVA (480 V <sub>ac</sub> )	3.0
June 2002	Edison/STM	Agrate, Italy	Semiconductor Processing Facility Voltage Sags - 2 Units	8.0 MVA (480 V <sub>ac</sub> )	3.0
April 2002	EDF	Paris, France	Voltage Sag Protection	8.0 MVA (400 V <sub>ac</sub> )	3.0



**SMES Deployment Status**

Table 12-3 summarizes the status of SMES deployment.

**Table 12-3**  
**Technology Status of SMES**

Application	MicroSMES for Power Quality	D-SMES for System Stability
Status	Commercial: several units installed as described in Table 12-1	Demonstration
Funding organizations	Private funding in US. Some government funding of potential applications by Japan and Germany	American Superconductor, Wisconsin Power System
Vendors	American Superconductor	American Superconductor
Major demonstrations	See Table 12-2	Northern Wisconsin power system
Lessons learned	Critical issues in terms of the power output and response time.	Early data indicates that D-SMES is effective in the Wisconsin application. Additional information is required on these and other installations.
Major development trends	American Superconductor has several units in the field at this time. However, they have standardized on the D-SMES installation as the standard product. At present there is only one vendor.	American Superconductor is prepared to deliver additional units and is actively searching for customers
Unresolved issues	Costs of SMES units relative to other PQ technologies.	Cost effectiveness of this application compared to other solutions.

**Developmental Costs**

The original development of SMES systems was for load leveling as an alternative to pumped hydroelectric storage. Thus, large energy storage systems were considered initially. Research and then significant development were carried out over a quarter century in the US, beginning in the early 1970s. This effort was mainly supported by the Department of Defense, the Department of Energy, and EPRI. Internationally, Japan had a significant program for about 20 years, and several European countries participated at a modest level. The Defense Department -sponsored Engineering Test Model (ETM) program funded \$72 M worth of design, engineering and test work between 1988 and 1994. In addition, the total international R&D related labor on SMES for load leveling up to the present is estimated to be about 500 person years, or about \$75M. Since no practical devices have been constructed or installed, material and construction costs will not increase this value significantly.

At several points during the SMES development process, researchers recognized that the rapid discharge potential of SMES, together with the relatively high energy related (coil)



costs for bulk storage, made smaller systems more attractive and that significantly reducing the storage time would increase the economic viability of the technology. Thus, there has also been considerable development on SMES for pulsed power systems. Though EPRI and government organizations have supported some of this effort, a great deal has been internally supported by industry. The total labor R&D in this area has been about 250 person years. In addition, several devices have been fabricated. We estimate that the combined international effort is on the order of \$50M for SMES systems for pulsed power, system stability, and for other rapid discharge applications.

## **T&D System Energy Storage Applications**

### **Select Applications for SMES Systems**

This section presents the select applications for which the SMES is suited and describes the key features of the SMES systems when configured to meet the requirements of those applications. Screening economic analyses have shown that SMES systems are potentially competitive for three of the single function applications described in detail in Chapter 3. The following list briefly summarizes and reiterates key requirements for all applications. Those for which SMES is best suited are enclosed by borders.

#### **Single Function Applications**

**Application A: Grid Angular Stability (GAS)** – mitigation of power oscillations by injection and absorption of real power at periods of 1 to 2 seconds. The reference duty cycle for analysis is standby for infrequent events characterized by 20 oscillatory cycles, cumulatively equivalent to a full power discharge (FPD) of 1-second duration; 1 event per day; 10 events per year. Valued at the cost of alternative solutions.

**Application B: Grid Voltage Stability (GVS)** – mitigation of degraded voltage by additional reactive power plus injection of real power for durations up to 2 seconds. The reference duty cycle for analysis is standby for infrequent events characterized by 1 second FPD, 1 event per day, 10 events per year. Valued at the cost of alternative solutions.

**Application C: Grid Frequency Excursion Suppression (GFS)** – “prompt” spinning reserve (or load) for mitigating load-generation imbalance. Requires energy storage to discharge real power for durations up to 30 minutes. The reference duty cycle for analysis is standby for infrequent events characterized by 15-minute FPD, 1 event per day, 10 events per year. Valued at the cost of alternative solutions.

**Application D: Regulation Control (RC)** – system frequency regulation in concert with load following. The reference duty cycle for analysis is characterized by continuous cycles equivalent to 7.5-minute FPD and charge cycle (triangular waveform), 2 cycles per hour deployed with 10 minutes advance notice. Valued at market rates.

**Application E: Spinning Reserve (SR)** – reserve power for at least 2 hours with 10 minute notice. The reference duty cycle for analysis is standby for infrequent events characterized by 2-hour FPD, 1 event per day, 10 events per year. Valued at market rates.

**Application F: Short Duration Power Quality (SPQ)** – capability to mitigate voltage sags (e.g., recloser events). The reference duty cycle for analysis is standby for infrequent events characterized by 5 seconds



FPD, 1 event per hour, 5 events per day, 100 events per year. Valued at the cost of alternative solutions.

**Application G: Long Duration Power Quality (LPQ)** – SPQ, plus capability to provide several hours reserve power. The reference duty cycle for analysis is standby for infrequent events characterized by SPQ plus standby for 4 hours FPD, 1 event per year. Valued at the cost of alternative solutions.

**Application H: 3-hr Load Shifting (LS3)** – shifting 3 hours of stored energy from periods of low value to periods of high value. The reference duty cycle for analysis is scheduled 3-hour FPD, 1 event per day, 60 events per year. Valued at market rates.

**Application I: 10-hr Load Shifting (LS10)** – shifting 10 hours of stored energy from periods of low value to periods of high value. The reference duty cycle for analysis is scheduled 10-hour FPD, 1 event per day, 250 events per year. Valued at market rates.

#### **Combined Function Applications (In the Order Noted)**

**Application C1:** Combined Applications C, A, B, D (GFS + GAS + GVS + RC)

**Application C2:** Combined Applications F, I, D, E (SPQ + LS10 + RC + SR)

**Application C3:** Combined Applications F, H, D, E (SPQ + LS3 + RC + SR)

**Application C4:** Combined Applications G, H, D, E (LPQ + LS3 + RC + SR)

**Application C5:** Combined Applications I, D, E (LS10 + RC + SR)

#### ***SMES System Compliance With Application Requirements***

The SMES product performance parameters discussed in the previous section were used to develop approximate sizes and operational parameters for systems meeting the requirements of the applications selected for SMES in the previous section. The key factors in sizing SMES systems are the power and energy requirements of the application. The D-SMES product line can be adapted for increased DC-link voltages and increased discharge durations, and two different configurations have been adapted for the three applications noted above. Performance aspects of SMES systems for the selected applications are described below and summarized in Table 12-4. The reference power for all applications is 10 MW<sub>ac</sub>.

- **Application A: Grid Angular Stability (GAS)** – This application requires that the system continuously detect and mitigate infrequent short duration, oscillatory events. D-SMES, adapted to 3000 V<sub>dc</sub> chopper voltage, was equipped with a Type I PCS and configured for this application to be capable of full power discharges for up to 1 second. The system will spend virtually its entire life in standby mode, for which standby SMES efficiency is calculated at 99.4%, attributed to continuous power for refrigeration and coil current losses at the PCS interface. The net system standby efficiency, including PCS losses, is 97.4%, and the projected life for this application is 20 years.



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- **Application B: Grid Voltage Stability (GVS)** – This application requires that the system continuously detect and mitigate infrequent voltage instabilities and provide short duration real power, as well as continuous reactive power. D-SMES, adapted to 3000 V<sub>dc</sub> chopper voltage, was equipped with a Type I PCS and configured for this application to be capable of real power discharges for up to 1 second, as well as to provide reactive power. The system will spend virtually its entire life in standby mode, for which standby SMES efficiency is calculated at 99.4%, attributed to continuous power for refrigeration and coil current losses at the PCS interface. The net system standby efficiency, including PCS losses, is 97.4%, and the projected life for this application is 20 years.
- **Application F: Short Duration Power Quality (SPQ)** – This application requires that the system continuously detect and mitigate infrequent PQ events lasting to up to 2 seconds. D-SMES, capable of full power discharges for up to 2 seconds, was equipped with a Type III PCS, based on 750V<sub>dc</sub> chopper voltage (pulse factor of 5) suitable for discontinuous IGBT converters. This system will also spend virtually its entire life in standby mode, for which standby SMES efficiency is calculated at 98.3%, attributed to continuous power for refrigeration and coil current losses at the PCS interface. The net system standby efficiency, including PCS losses, is 96.3%, and the projected life for this application is 20 years.



**Table 12-4  
SMES System Compliance With Application Requirements**

Applications	Single Function		
	App A: GAS -- 1 sec FPD equivalent over 20 oscillations per event, 10 events/yr, 1 event/d	App B: GVS -- 1 sec FPD per cycle, 10 events/yr, 1 event/d	App F: SPQ -- 2 sec FPD per cycle, 100 events/yr, 5 events/d, 1 event/hr
<b>Model Selection</b>			
Type	DSMES-3KV	DSMES-3KV	DSMES-480V
Pulse Factor	NA	NA	5.0
Chopper Voltage ( $V_{min}$ )	3,000	3,000	750
Maximum DOD, %	100%	100%	100%
Replacement Interval, yr	20	20	20
<b>PCS Selection</b>			
PCS Type (Chapter 5)	I	I	III
<b>Duty Cycles</b>			
<b>Grid Support or Power Quality (GS or PQ)</b>			
Power, MW	10	10	10
Event Duration, sec	1.0	1.0	2.0
<b>Summary System Data</b>			
Standby Hours per Year	8,760	8,760	8,760
System Net Efficiency, % (See Note)	97.4%	97.4%	96.3%
SMES Standby Efficiency, %	99.4%	99.4%	98.3%
PCS Standby Efficiency, %	98.0%	98.0%	98.0%
System Footprint, MW/sqft (MW/m <sup>2</sup> )	0.0051 (0.055)	0.0051 (0.055)	0.0044 (0.047)
SMES Footprint, MW/sqft (MW/m <sup>2</sup> )	0.015 (0.16)	0.015 (0.16)	0.01 (0.11)
<p>Note: System net efficiency includes losses for energy conversion and system standby expressed on an annual basis, i.e., one minus inefficiency, where inefficiency equals the ratio of annual energy losses to the product of system rated power times 8760 hours, expressed in percent.</p>			



## Benefit and Cost Analyses

### SMES System Pricing and Integrated System Costs

American Superconductor has adapted product lines in response to market forces over the past few years, which saw a rapid rise in demand for power quality equipment in the late 1990's, and subsequent abrupt decline more recently. During this period, demand for utility grid support systems has been constrained to local congestion issues. In response to this market, American Superconductor has brought forth the D-VAR product line, which focuses on demand for reactive power products. D-SMES based products remain an important element of their product portfolio.

For the Handbook's reference deployment date of 2006 and rating of  $10\text{MW}_{ac}$ , nominal unit prices supplied by American Superconductor [4] for  $3\text{MW}_{ac}$ , 3 MJ D-SMES products have been applied to the  $10\text{MW}_{ac}$  GAS and GVS (10 MJ, DSMES-3KV) and SPQ (20 MJ, DSMES-480V) applications.<sup>19</sup> No replacement modules are projected over the 20-year project lifetimes. The resultant SMES prices for GAS, GVS and SPQ applications used in the benefit-cost assessments herein are:

SMES Unit	2006 Prices, K\$
DSMES-3KV	\$2030
DSMES-480V	\$3030

The scope of supply corresponding to the above units includes refrigeration and refrigeration power supply, the magnet (coil) and magnet control system, and the DC-chopper (magnet interface to the inverter), plus technical support for system integration, installation and startup.

The cost of integrated systems is obtained by combining the cost of the SMES scope of supply with the appropriate PCS and BOP costs as described in Chapter 5. The PCS and BOP costs shown in Table 12-5 are based on the methodology described in Chapter 5. SMES systems for the GAS and GVS applications use Type I PCS as a result of relative high ( $3000\text{V}_{dc}$ ) DC-link voltage, while the system for SPQ uses a Type III "discontinuous" IGBT-based PCS. Since the cost of exterior enclosures is included in the SMES scope of supply, the cost of exterior space is included at \$20 per square foot. SMES disposal costs are assumed to be negligible since no hazardous materials are involved. In accordance with the provisions of Chapter 5, BOP costs are assigned at \$50/kW because SMES is commercially available as a fully integrated system.

<sup>19</sup> The designations DSMES-3KV and DSMES-480V are used for the purposes of describing adaptations used in this Handbook and are not American Superconductor designations.



Fixed O&M costs for the PCS are based on \$2/kW as required by provisions in Chapter 5, and SMES maintenance is projected at \$5/kJ. Representative maintenance activities include:

- Servicing refrigeration equipment
- Confirming the operability of system protective devices
- Calibrating sensors and instrumentation
- Inspecting for unusual vibrations, noise or odors
- Inspecting for abnormal conditions of connecting cables and piping
- Inspecting insulation resistance

No disposal costs are included since all materials can be treated as industrial waste.

Year	1990	1991	1992
Operating Costs	100	100	100
Maintenance	50	50	50
Depreciation	200	200	200
Interest	100	100	100
Taxes	50	50	50
Total	500	500	500



**Table 12-5  
Capital and Operating Costs for SMES Systems**

Applications	Single Function		
	App A: GAS -- 1 sec FPD equivalent over 20 oscillations per event, 10 events/yr, 1 event/d	App B: GVS -- 1 sec FPD per cycle, 10 events/yr, 1 event/d	App F: SPQ -- 2 sec FPD per cycle, 100 events/yr, 5 events/d, 1 event/hr
SMES Capacity, MWhac	0.003	0.003	0.006
PCS Initial Cost, \$/kW	120	120	150
BOP Initial Cost, \$/kW	50	50	50
SMES Initial Cost \$/kW	207	207	309
SMES Initial Cost \$/kWh	740,000	740,000	560,000
Total Capital Cost, M\$	3.8	3.8	5.1
O&M Cost -- Fixed, \$/kW-year	14.5	14.5	22.2
O&M Cost-- Variable, \$/kW-year	8.7	8.7	12.4
NPV SMES Disposal Cost, \$/kW	0.0	0.0	0.0
<p>Note: The total initial cost may be calculated in two ways:</p> <ol style="list-style-type: none"> <li>1. By multiplying the sum of PCS, BOP and Battery initial costs expressed in \$/kW by the reference power,</li> <li>2. OR by multiplying the sum of PCS and BOP expressed in \$/kW by the reference power and then adding the product of Battery Initial cost expressed in \$/kWh and the Battery Capacity</li> </ol>			



### **Lifecycle Benefit and Cost Analysis for SMES Systems**

Further insight to the value of energy storage can be gained through lifecycle cost analyses using a net present value (NPV) methodology and comparison with alternatives. For the convenience of the reader, the financial parameters and electric rate structure set forth in Chapters 4 and 5 and used in the analyses are summarized in Table 12-6 and Table 12-7.

**Table 12-6**  
**Financial Parameters**

Dollar Value	2003
System Startup	June 2006
Project Life, years	20
Discount Rate (before tax), %	7.5
Property Taxes & Insurance, %/year	2
Fixed Charge Rate, %/year	9.81

**Table 12-7**  
**Electric Rates**

Load Shifting On Peak Period	3	10
Number Cycles per year	60	250
On-Peak Energy, \$/MWh	120	80
Off-Peak Energy, \$/MWh	20	
Yearly Average Energy Charge, \$/MWh	38	
Regulation Control, \$/MW-Hour (power), \$/MWh	16	
Spinning Reserve, \$/MW-Hour (power), \$/MWh	3	
Transmission Demand Charge, \$/kW-mo	5	

The results of lifecycle cost benefit analyses of select SMES applications are summarized in Table 12-8 and discussed below. The bases and methodology used in valuing energy storage applications is described in detail in Chapter 4. The details of the cost benefit analysis for each application are discussed below.

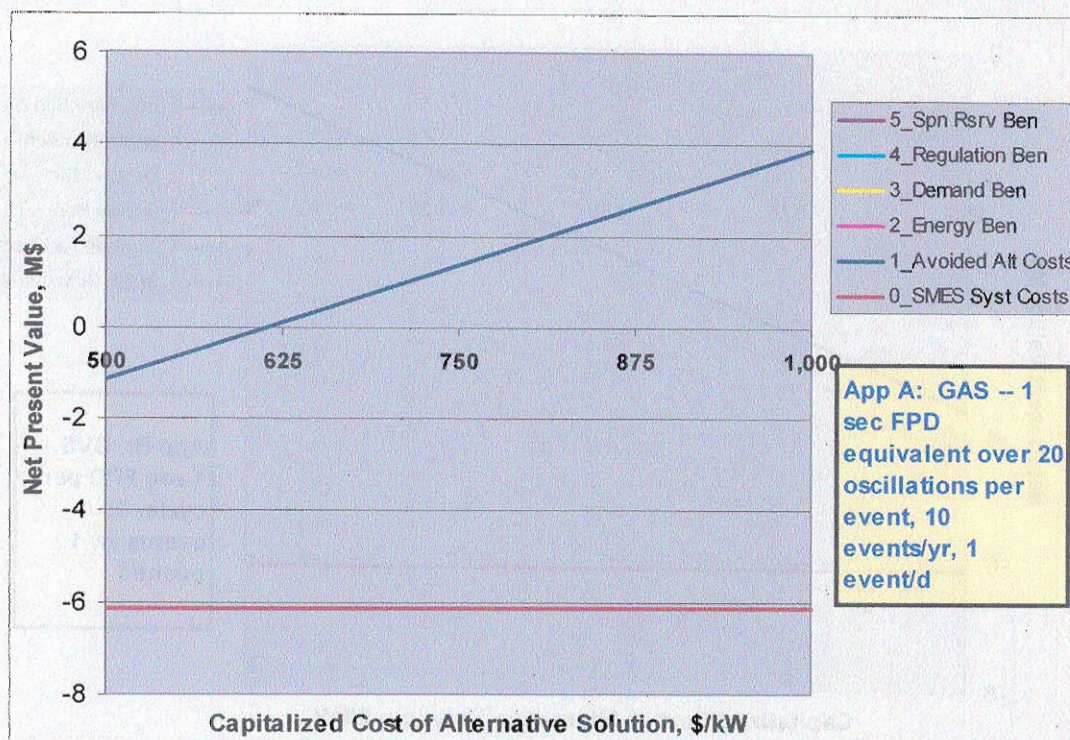


**Table 12-8**  
**Summary of Benefit and Cost Analyses of SMES Battery Systems**

Applications	Single Function		
	App A: GAS -- 1 sec FPD equivalent over 20 oscillations per event; 10 events/yr, 1 event/d	App B: GVS -- 1 sec FPD per cycle, 10 events/yr, 1 event/d	App F: SPQ -- 2 sec FPD per cycle, 100 events/yr, 5 events/d, 1 event/hr
Alt Solution Value, \$/kW	750	500	1,000
Initial Installed Cost, M\$	3.76	3.76	5.11
Total Costs, M\$	(6.1)	(6.1)	(8.6)
Total Benefits, M\$	7.50	5.0	10.0
Benefit to Cost Ratio	1.23	0.82	1.16
NPV, M\$	1.4	(1.1)	1.4
SMES Module	DSMES-3KV	DSMES-3KV	DSMES-480V
SMES 2006 Price, (\$K, FOB)	2,030	2,030	3,030
SMES Price for NPV=0, (\$K, FOB)	3,180	1,100	4,160

- Application A: Grid Angular Stability (GAS) – This application was evaluated on the assumption that an alternative solution capable of mitigating GAS events can be obtained for net capitalized costs of about \$750/kW, including acquisition, fixed and variable O&M, and property taxes and insurance costs. As shown in Table 12-8, this application yields a NPV of \$1.4 million for an initial investment of about \$3.8 million on this basis. As a measure of the sensitivity of NPV with respect to alternative solution costs, Figure 12-9 illustrates the change in NPV over a range of \$500 to \$1000/kW and shows that SMES systems will compete favorably against alternative solutions with net capitalized costs in excess of about \$610/kW. As an additional indicator of NPV sensitivity with respect to the cost of energy storage, if the price of DSMES-3KV were increased from \$2.03 to \$3.18 million, the NPV would equal zero, i.e., costs and benefits would be equal.

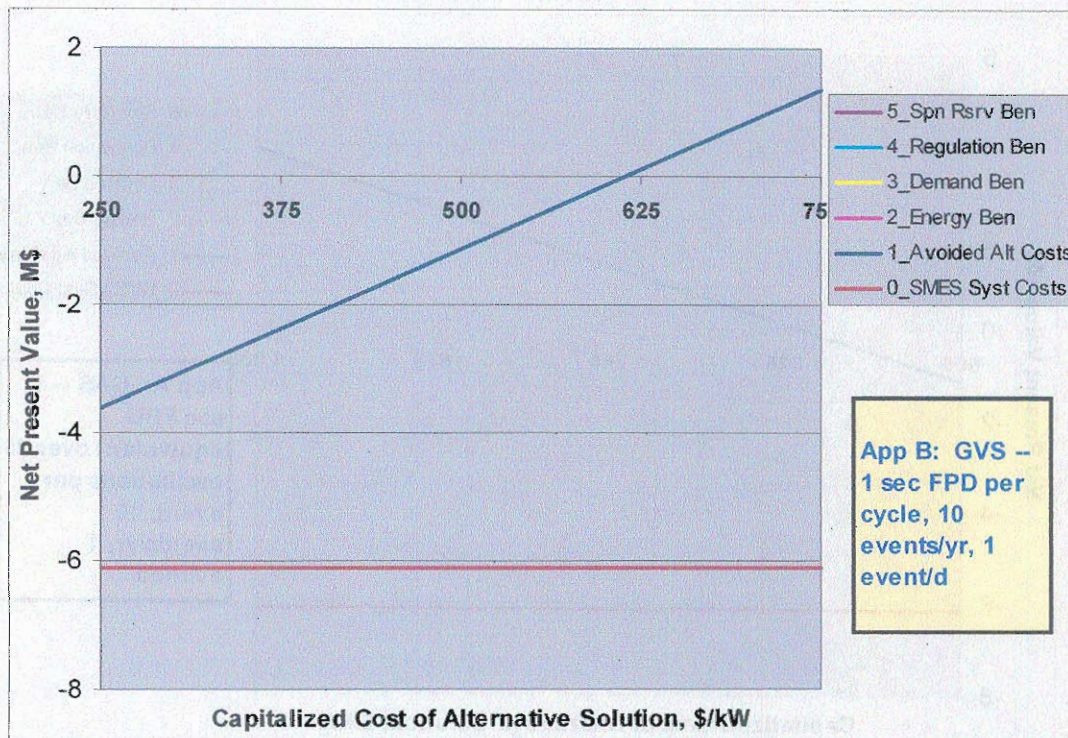




**Figure 12-9**  
Application A: SMES System NPV vs Cost of Alternative Solution

- Application B: Grid Voltage Stability (GVS) – This application was evaluated on the assumption that an alternative solution capable of mitigating GVS events can be obtained for net capitalized costs of about \$500/kW, including acquisition, fixed and variable O&M, and property taxes and insurance costs. As shown in Table 12-8, this application yields a negative NPV of (\$1.1) million for an initial investment of about \$3.8 million on this basis. However, the benefit to cost ratio is about 0.8, and SMES is deemed to be marginally competitive in that it should be considered in circumstances where its intrinsic properties (e.g., its relatively small space requirements) are of high value. As a measure of the sensitivity of NPV with respect to alternative solution costs, Figure 12-10 illustrates the change in NPV over a range of \$250 to \$750/kW and shows that SMES systems will compete favorably against alternative solutions with net capitalized costs in excess of about \$610/kW. As an additional indicator of NPV sensitivity with respect to the cost of energy storage, if the price of DSMES-3KV were decreased from \$2.03 to \$1.1 million, the NPV would equal zero, i.e., costs and benefits would be equal.





**Figure 12-10**  
**Application B: SMES System NPV vs Cost of Alternative Solution**

- Application F: Short Duration Power Quality (SPQ) – This application was evaluated on the assumption that an alternative solution capable of mitigating SPQ events can be obtained for net capitalized costs of about \$1000/kW, including acquisition, fixed and variable O&M, and property taxes and insurance costs. As shown in Table 12-8, this application yields a NPV of \$1.4 million for an initial investment of about \$5.1 million on this basis. As a measure of the sensitivity of NPV with respect to alternative solution costs, Figure 12-11 illustrates the change in NPV over a range of \$500 to \$1500/kW and shows that SMES systems will compete favorably against alternative solutions with net capitalized costs in excess of about \$860/kW. As an additional indicator of NPV sensitivity with respect to the cost of energy storage, if the price of GAS SMES were increased from \$3.03 to \$4.16 million, the NPV would equal zero, i.e., costs and benefits would be equal.



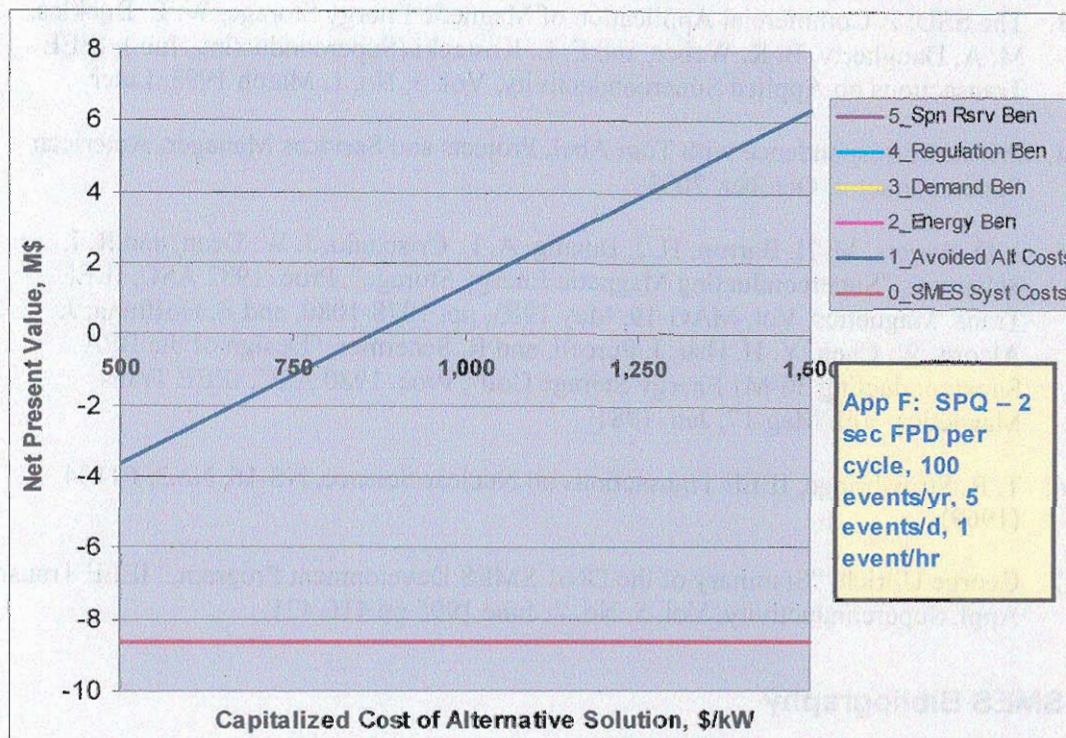


Figure 12-11  
Application F: SMES System NPV vs Cost of Alternative Solution

### Interpreting Results From Benefit-Cost Analyses

In general, SMES systems are expected to be competitive for grid support applications.

The reader is reminded that the foregoing analyses are intended as a guide to the initial consideration of energy storage options, and that these analyses are based on representative electric rates and costs for alternative solutions as described in Chapter 4. The assumptions used herein should be reviewed in light of project specific applications, alternative solutions, electric rates and financial parameters.

### References

1. M. Ferrier, "Stockage d'energie dans un enroulement supraconducteur", in *Low Temperature and Electric Power*, London, England: 1970, Pergamon, pp. 425-432."
2. E.F. Hammel, W.V. Hassenzahl, W.E. Keller, T.E. McDonald, and J.D. Rogers, "Superconducting Magnetic Energy Storage for Peakshaving in the Power Industry," Los Alamos Scientific Laboratory Report LA-5298-MS, 1973.



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3. The SSD: A Commercial Application of Magnetic Energy Storage, W. E. Buckles, M. A. Daugherty, B. R. Weber, and E. L. Kostecky (Superconducting, Inc.), IEEE Transactions on Applied Superconductivity, Vol. 3, No. 1, March 1993. Later
4. Private correspondence with Tom Abel, Projects and Services Manager, American Superconductor, October, 2003
5. J. D. Rogers, M. H. Barron, H. J. Boenig, A. L. Criscoulo, J. W. Dean, and R. I. Schermer, "Superconducting Magnetic Energy Storage", Proc. 1982 ASC, IEEE Trans. Magnetics, Vol. MAG-19, May 1983, pp. 1078-1080, and E. Hoffman, J. Alcorn, W. Chen, Y. H. Hsu, J. Purcell, and R. Schermer, "Design of the BPA Superconducting 30-MJ Energy Storage Coil", Proc. 1980 ASC, IEEE Trans. Magnetics, Vol: Mag-17, Jan. 1981.
6. T. R. Strowbridge, IEEE Transactions on Nuclear Science, NS-16, No.2, P1104 (1969)
7. George Ullrich, "Summary of the DNA SMES Development Program," IEEE Trans. Appl. Superconductivity, Vol. 5, No. 2, June 1995 pp 416-421.

### **SMES Bibliography**

A series of conferences and journals contain innumerable articles on superconductivity and SMES technology, including:

- The Applied Superconductivity Conference is held in North America every even year. The proceedings of recent conferences are published in the IEEE Transactions on Applied Superconductivity. They contain considerable information on applicable superconducting materials and on SMES technology.
- The Material Research Society meets at least once per year and the proceedings of these meetings contain considerable information on the status of basic research in the area of superconductivity.
- The American Physical Society (APS) has several national and regional meetings each year that include sessions on LTS and HTS materials. In addition, there are several journals published by the American Institute of Physics, of which the APS is a member, that include articles on superconductivity.

### **Seminal Articles and Books**

- The first paper on the phenomenon of superconductivity was:  
H. K. Onnes, Leiden Comm. 120b, 122b, 124c (1911)
- The first paper on high temperature superconductivity was:  
J. G. Bednorz and K. Mueller, Z. Physik B64, 189 (1986)



- The accepted book that is used to develop magnet and conductor designs is: Martin N. Wilson, *Superconducting Magnets* Oxford Science Publications, Oxford, UK, 1983.
- The original article that related stored energy and support structure was: R. Clausius, "On a Mechanical Theorem Applicable to Heat," *Phil. Mag.* S-4, Vol. 40, pp 12-127, 1870.

## **Early Articles and Papers On SMES**

Early articles and papers on SMES include the following:

- H. A. Peterson, N. Mohan, and R. W. Boom, "Superconductive Energy Storage Inductor-Convertor Units for Power Systems", *IEEE Trans. Power Systems*, *IEEE Trans. Power App. Syst.*, Vol. PAS-94, No. 4, July-August 1975.
- W.V. Hassenzahl, "Will Superconducting Magnetic Energy Storage be Used on Electric Utility Systems?" *IEEE Transactions on Magnetics*, MAG-11, No. 2, 1975, pp. 482-88 (LA-UR-74-1470).
- J.D. Rogers, W.V. Hassenzahl, and R.I. Schermer, "1 GWh Diurnal Load levelling Superconducting Magnetic Energy Storage System Reference Designs," *Los Alamos Scientific Laboratory LA- 7885-MS Vols. I-VIII*, September 1979.
- William V. Hassenzahl, "Superconducting Magnetic Energy Storage," *Proc. of the IEEE*, 71 (September 1983), pp. 1089-98.

The first report that considered a diurnal SMES plant for other utility applications (in this case spinning reserve) was:

- W.V. Hassenzahl, B.L. Baker, and W.E. Keller, "The Economics of the Superconducting Magnetic Energy Storage Systems for Load levelling: a Comparison with Other Systems," *Los Alamos Scientific Laboratory Report LA-5377-MS*, September 1973.

Early reports on the need for energy storage and the use of SMES for system stability include:

- R. L. Cresap, W. A. Mittelstadt, D. N. Scott, and C. W. Taylor, "Operating Experience with Modulation of the Pacific HVDC Intertie", *IEEE PAS Summer Meeting*, Mexico City 1977.

EPRI supported a series of studies on SMES in the early 1980's. In 1986, EPRI decided to pursue the design and construction of an engineering test model ETM that stored about 100 MWh. This model stored about 2 percent of the energy of a full-scale diurnal SMES. At about the same time, the Strategic Defense Initiative (SDI) required a pulsed energy storage system with capacities greater than 1000 MWh and with discharge times of about 30 minutes. Much of the development of the diurnal SMES application over the next 6



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### *Superconducting Magnetic Energy Storage*

years was based on a dual use concept. Several reports and papers related to this effort are given below.

- W. V. Hassenzahl, "Superconducting Magnetic Energy Storage", IEEE Trans. on Magnetics Vol. 24 No.2, March 1989, pp 750-758.
- Hassenzahl, W. V., R. B. Schainker, and T. M. Peterson, "The Superconducting Energy Storage ETM", Modern Power Systems Review, Vol. 11-3, pp 27-31, March 1991, London.

### **Other Articles In The Design And Use Of SMES**

Other articles of interest in the design and use of SMES include:

- Facts with Energy Storage: Conceptual Design Study, EPRI, Palo Alto, CA: 1999. TR-111093
- W. V. Hassenzahl, "Considerations against force compensated coils", IEEE Trans. on Magnetics, Vol. 24 No.2, March 1989, pp 1854-1857.
- J. F. Picard, C. Levillain, P. G. Therond (Electricité de France, R&D division), SCENET, "Advantages and perspectives of SMES", 2nd Workshop on Power Applications of Superconductivity, November 1997.
- C. Levillain, P. G. Thérond (Electricité de France), "Minimal Performances of High T<sub>c</sub> Wires for Cost Effective SMES Compared with Low T<sub>c</sub>'s", IEEE Transactions on Magnetics, Vol. 32, No. 4, July 1996.
- Micro Superconducting Magnetic Energy Storage (SMES) System For Protection of Critical Industrial and Military Loads, A. K. Kalafala, J. Bascuñan, D. D. Bell, L. Blecher, F. S. Murray, M. B. Parizh, M. W. Sampson, and R. E. Wicox (Intermagnetics General Corporation), IEEE Transactions on Magnetics, Vol. 32, No. 4, July 1996.
- Operation of a Small SMES Power Compensator, K. P. Juengst, H. Salbert (Forschungszentrum Karlsruhe, Institut für Technische Physik), O. Simon (Elektrotechnisches Institut (ETI), Universität Karlsruhe), Proceedings from European Conference on Applied SC, July 1997, Eindhoven.

### **High Temperature Superconductors for SMES**

Since their discovery in 1986, high temperature superconductors have been proposed for SMES applications. Some of the papers on the subject are listed here:

- Prospects for the Use of High T<sub>c</sub> Materials for Superconducting Magnetic Energy Storage, William V. Hassenzahl, Proceedings of EPRI Workshop on High-Temperature Superconductivity, April 1988, EPRI EL/ER-5894P-SR



- Conceptual Design Study of Superconducting Magnetic Energy Storage Using High Temperature Superconductors, S. M. Schoenung (W. J. Schafer Associates), R. L. Fagaly, M. Heiberger, R. B. Stephens, J. A. Leuer, R. A. Guzman, E. R. Johnson (General Atomics), J. Purcell, L. Creedon, J. R. Hull (Advanced CryoMagnetics), Final Report to DOE February 1993, DOE/CE/34019-1
- Superconducting Magnetic Energy Storage (SMES) Using High-Temperature Superconductors (HTS), Susan M. Schoenung, Robert L. Bieri (W. J. Schafer Associates), Final Report for Sandia National Laboratory May 1994, Subcontract AG-5265
- S. S. Kalsi, D. Aided, B. Connor, G. Snitchler, J. Campbell, R. E. Schwall (American Superconductor Corporation), J. Kellers (American Superconductor Europe), Th. Stephanblome, A. Tromm (Gesellschaft für Innovative Energieumwandlung und Speicherung GmbH), P. Winn (Applied Engineering Technologies), "HTS SMES Magnet Design and Test Results", IEEE Transactions on Applied Superconductivity, Vol. 7, No. 2, June 1997.
- R. Mikkonen, M. Lahitnen, J. Lehtonen, and J. Paasi (Tampere University of Technology), B. Conner, S. S. Kalsi (American Superconductor), "Design Considerations of a HTS  $\mu$ -SMES", European Conference on Applied SC, July 1997

### **Conference Proceedings**

As mentioned earlier, one of the richest sources of information on SMES development are the proceedings of the Applied Superconductivity Conferences. The most recent conference was August 4-9, 2002, and the proceedings will be published by the IEEE in April of 2003. Titles of some of the papers on SMES in this conference are given below.

- A 100 MJ SMES Demonstration at FSU-CAPS, C.A. Luongo, T. Baldwin, FSU-CAPS; C.M. Weber, P. Ribeiro, BWX Technologies.
- Magnet Power Supply with Power Fluctuation Compensating Function Using SMES for High Intensity Synchrotron, T. Ise, Y. Kobayashi, S. Kumagai, Osaka University; H. Sato, T. Shintomi, KEK.
- Impact of Micro-SMES on Power Flow, J. Liu, M.M.A. Salama, R.R. Mansour, University of Waterloo.
- Design of a 150 kJ High-Tc SMES for a 20 kVA Uninterruptible Power Supply System, R. Kreutz, H. Salbert, D. Krischel, A. Hobl, C. Radermacher, ACCEL Instruments GmbH; N. Blacha, AEG SVS GmbH; P. Behrens, EUS GmbH; K. Dütsch, E.ON Netz GmbH.
- Fabrication and Test of a Superconducting Coil for SMES System, H.J. Kim, K.C. Seong, J.W. Cho, S.W. Kim, Y. K. Kwon, Korea Electrotechnology Research Institute.



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- Fabrication of a 4kJ High-Tc Superconducting Pulse Coil Wound with a Bi2223 Wire for SMES, H. Hayashi, H. Kimura, Y. Hatabe, K. Tsutsumi, Kyushu Electric Power Co., Inc; M. Iwakuma, K. Funaki, Kyushu University; A. Tomioka, T. Bohno, Y. Yagi, Fuji Electric Co., Ltd.
- A 5 kJ HTS SMES Magnet System with Temperature Variation, X.H. Jiang, Y.C. Lai, Dept. of Electrical Engineering, Tsinghua University; J. Yang, N.Q. Jin, Institute of Electrical Engineering, Chinese Academy of Sciences; Z.G. Cheng, Baoding Tianwei Group Co. Ltd.
- HT-SMES Operating at Liquid Nitrogen Temperatures for Demonstrating Power Conditioning, A. Friedman, N. Shaked, E. Perel, F. Gartzman, M. Sinvani, Y. Wolfus, Y. Yeshurun, Center of Superconductivity, Bar-Ilan University.

### **Refrigeration Systems**

The two articles below show the cost vs. size dependence of the refrigeration systems for superconducting magnets.

- M. A. Green, R. A. Byrns, and S. J. St. Lorant, "Estimating the Cost of Superconducting Magnets and the Refrigerators Needed to Keep Them Cold". *Advances In Cryogenic Engineering*, Vol 37, Feb, 1992 Plenum Press, New York.

### **Coil Geometries**

Several different geometries have been considered for SMES. They are described in the report below. In general, the solenoid is simplest to build and is the lowest price. However, other designs might be more effective for specific applications, particularly those where the stray magnetic field is important.

- W. V. Hassenzahl, "A Comparison of the Conductor Requirements for Energy Storage Devices Made with Ideal Coil Geometries", *IEEE Transactions on Magnetics*, VOL. 25, No.2 March 1989.

### **Other Reports on SMES Applications and Benefits**

- W.V. Hassenzahl, B.L. Baker, and W.E. Keller, "The Economics of the Superconducting Magnetic Energy Storage Systems for Load levelling: a Comparison with Other Systems," Los Alamos Scientific Laboratory Report LA-5377-MS, September 1973.
- "Reassessment of Superconducting Magnetic Energy Storage (SMES) Transmission System Benefits", *Power Systems Engineers*, EPRI Report 1006795, March 2002.
- J. DeStees, et al "Benefit/Cost Comparisons of SMES in System-Specific Application Scenarios," *Proc. World Congress on Superconductivity*, Munich, Germany, September, 1992.



- S. Schoenung, "Superconducting Magnetic Energy Storage Benefits Assessment for Niagara Mohawk Power Corporation," report prepared for Oak Ridge National Laboratory, DE-AC05-84OR21400, 1994.
- Zaininger, SAND98-1904 (SMUD Wind and PV study)
- "The Market Potential for SMES in Electric Utility Applications," prepared by Arthur D. Little for Oak Ridge National Laboratory, Report No. ORNL/Sub85-SL889/1, 1994.
- S. Schoenung, J. Badin, J. Daley, "Commercial Applications and Development Projects for Superconducting Magnetic Energy Storage," Proc. of the American Power Conference, Chicago, 1993.



