Final Report for

WORKSHOP ON TERRESTRIAL ENERGY STORAGE AND GROUND SYSTEMS FOR SPACE SOLAR POWER SYSTEMS

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WORKSHOP ON TERRESTRIAL ENERGY STORAGE AND GROUND SYSTEMS FOR SPACE SOLAR POWER SYSTEMS

EXECUTIVE SUMMARY

As part of the Space Solar Power (SSP) Concept Definition Study conducted by NASA, a workshop on terrestrial energy storage and ground systems for the SSP systems was held at Auburn University, Alabama. In this workshop, several types of terrestrial energy storage systems that could potentially be used in a SSP system were identified. Among the options considered were compressed-air energy storage (CAES), inertial energy storage (flywheels), superconducting magnetic energy storage (SMES), electrochemical energy storage (batteries and supercapacitors), and pumped hydro energy storage. Also, issues regarding the interfaces between the rectenna and a local energy storage system as well as between the rectenna and/or energy storage system and the utility power grid were discussed. Each of these energy storage options was investigated to determine the feasibility of implementing it into a space solar power system concept. Issues included in the evaluation were the scaling potential of a particular technology to the level required for the SSP system, achievable energy and power densities, system performance, lifetime, required infrastructure, site restrictions, and cost (both capital and recurring costs). The terrestrial energy storage requirements for the SSP system were identified as that being necessary to supply the 1.2 GW power level of the SSP system during brief outages of 10 minutes (200MW-hrs) and longer outages of 4 hours (4.8 GW-hrs). Each technology was considered for use in either of these two scenarios. The compressed-air energy storage and pumped-hydro systems are currently used by utility companies for load leveling applications. These systems are capable of operating at the energy storage levels required for the SSP system; however, there are still some issues concerning the power requirements. The other systems have not yet been demonstrated on the scale required for these utility applications.

The recommendations arising from the workshop were to further study and identify the energy storage requirements for the SSP system and then analyze each of the energy storage options within the context of these parameters. The state-of-the-art for each technology would first have to be determined, and then the potential for using them in the SSP system would be identified. Parameters included in this analysis should be the energy storage levels and power delivery capability. Also, electrical performance, economic and environmental issues should be

considered such that various technologies could be compared and recommendations as to which systems should be developed for possible future implementation in the SSP system could be made.

WORKSHOP OBJECTIVES

The objectives of the workshop were to review the current state-of-the-art in terrestrial energy storage systems and to determine their potential to be used in a SSP system. The goals were to assess the range of energy storage systems applicable to SSP and identify technical and theoretical limitations for each technology studied. Recommendations as to the most cost effective systems for further study and the approaches to overcome identified technical barriers were also to be made. Approaches that could be used to interface the SSP system with the power grid and energy storage systems were also discussed.

INTRODUCTION

Terrestrial energy storage systems for the SSP system were evaluated that could maintain the 1.2 GW power level during periods of brief outages from the solar powered satellite (SPS). Short-term outages of ten minutes and long-term outages up to four hours have been identified as "typical" cases where the ground-based energy storage system would be required to supply power to the grid. These brief interruptions in transmission could result from performing maintenance on the solar power satellite or from safety considerations necessitating the power beam be turned off. For example, one situation would be to allow for the safe passage of airplanes through the space occupied by the beam. Under these conditions, the energy storage system needs to be capable of storing 200 MW-hrs and 4.8 GW-hrs, respectively. The types of energy storage systems to be considered include compressed air energy storage, inertial energy storage, electrochemical energy storage, superconducting magnetic energy storage, and pumped hydro energy storage. For each of these technologies, the state-of-the-art in terms of energy and power densities were identified as well as the potential for scaling to the size systems required by the SSP system. Other issues addressed included the performance, life expectancy, cost, and necessary infrastructure and site locations for the various storage technologies.

ENERGY STORAGE OPTIONS

The general types of energy storage systems are listed in Table 1 along with the energy storage medium and the storage and conversion technology associated with each type of storage system. The energy storage options that may be capable of storing this amount of required energy include CAES, flywheels, SMES, electrochemical storage, and pumped hydro energy storage systems. The state-of-the-art and the potential for application in the SSP system were addressed for each of these storage options. Some of these technologies have already demonstrated the ability to store this amount of energy, though it is not clear if they are capable of operating at the power levels required to accommodate the incident power beam from the SPS. A brief description of each energy storage system is included below, along with issues that will need to be addressed for each particular technology to achieve the energy and power requirements for the Space Solar Power system.

Table 1. General Energy Storage Systems

Storage Type	Storage Medium	Storage Technology	Conversion Technology
Fluids	Water Air	Dams Caverns	Motor-generator Driven pump-turbine
Inertial	Rotating Mass	Flywheel	Alternator/generator
Magnetic	Magnetic Field	Superconducting coil	Thyristor Inverter/Rectifier
Chemical	Electrode/electrolyte	Battery, Capacitor, Fuel Cell	Thyristor Inverter/Rectifier

Compressed Air Energy Storage

Gases are, in general, far more compressible than other forms of matter. Consequently, for large-scale energy storage, they have been investigated for intermediate storage more than other forms of "elastic" energy storage techniques. Compressed gas energy storage is commonplace and has many practical applications from "air tools" to the initial stage of underwater ballistic missile launch. Storage up to the gigajoule range can be readily accommodated in steel storage

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containers. For terrajoule storage, there are several options such as underground in salt domes, rock formations, and porous rock aquifers. For these systems, air is compressed and stored in the caverns during times of minimal load on the power system. During periods when peak power is required, the compressed air is released to a combustor and mixed with oil or gas. This mixture burns and is used to drive gas turbines and generators.

The storage volumes for caverns of this type can be as large as half a million cubic meters and, at relatively modest pressures of 10^7 N/m^2, these large caverns can store terrajoules. The electric utility companies currently have one such facility operational in McIntosh, Alabama and another in Huntorf, Germany. The McIntosh facility is a 110-MW system capable of storing 4.3 x 10^{12} J. This facility began operating in September of 1991 and cost approximately $65M to build. The Huntorf facility is a 290 MW system capable of storing 0.9 x 10^{12} J. It began operating in 1978. Both of these facilities have demonstrated an excellent history of service and reliability. Other storage systems of this type in the 200 MW class are currently under construction and several more are contemplated in Japan, Russia, and Israel. Issues concerning the response time of these storage systems will be critical to their credibility for use in the SSP system. Also, the location of suitable underground storage caverns could limit the availability of these systems.

Pumped Hydro Energy Storage

Pumped hydro energy storage is the most widespread energy storage technology for utility applications today. In this method, water is pumped uphill during offpeak times to an elevated reservoir, and, during peak times, the water is released to flow to a lower reservoir where the stored energy is used to drive turbines. There are 37 such facilities operating in the United States with power levels in the 500-2000 MW range. This technology is well established and has been used for decades in the utility power industry. However, to be economically feasible, the facilities must be large. This requires long lead times for construction and results in relatively high capital costs for constructing the reservoirs. Also, the large land area required for such a facility has led to significant opposition from environmental groups that pose a formidable opponent to developing these sites. In general, the cost of these pumped hydro energy storage systems is approximately twice that for a comparable CAES system.

Superconducting Magnetic Energy Storage (SMES)

The phenomenon of superconductivity allows the construction of an electrical energy storage systems based upon magnetic fields with minimal losses. Since the phenomenon of superconductivity is observed only at low temperature, there is a rather large cryogenic storage system that must always accompany energy storage units of this type. In general, the operating temperature of cryogenic superconducting storage systems is in the range of 5-20K. The emergence of the high temperature superconductors may extend the range of operability to as high as 77 K. Basically, an inductor is wound from the appropriate superconductor and a current made to flow, establishing a magnetic field within the coil structure. For minimal fringing and interference effects, most of these storage units are in the shape of a toroid. The energy stored in such a unit is given by:

$$E = \frac{1}{2}LI^2$$

where L is the inductance of the coil and I is the current through the coil.

Since superconductors have a critical current, there is a maximum operating current for any system. Similarly, geometry and mass limit the values of inductance, L, which might be achieved. Inductive energy stores suffer from the fact that there is a large force generated proportional to the square of the value of the magnetic field. Consequently the cryogenic container shown in Figure 1 must be able to handle considerable stress. When the energy is needed for delivery to the grid, suitable output circuitry must be employed to divert the energy stored in the SMES to the load.
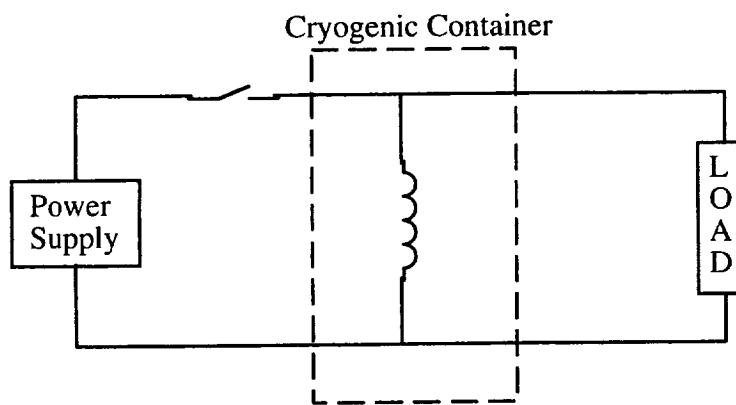

Figure 1. Superconducting Energy Storage Circuit Schematic

The state-of-the-art in SMES systems for commercially available units is for stored energy on the order of 1 MJ and a power level of 1 MW. The ballpark cost for these systems is approximately $0.5M. For most of the power quality applications that these units are being considered, they are looking for 10s of MJ stored energy at 10s of MW power levels. Prior design efforts for the Department of Defense in the early 1990s looked at a system capable of storing 20 MWhr and operating at a power level of 400 MW. The requirements of the SSP system for a 200 MWhr system at 1.2 GW are thought to be within the realm of these system designs, although the peak power level may be pushing the limits of this technology. The cost of these systems can be driven either by the energy storage requirements or by the power levels and would depend on the specific design parameters used for a system.

Inertial Energy Storage (Flywheels)

Kinetic energy is associated with any mass moving at a velocity **v**. In general, it is hard to extract energy from a system where the motion is linear. However, kinetic energy stored in rotational motion is high in energy density, limited by the ultimate tensile strength of the material comprising the storage medium. Maraging steel has a tensile strength on the order of 2700 meganewtons/m^2 and a density on the order of 8000 kg/m^3. By contrast, kevlar fibers have a tensile yield strength on the order of 1800 meganewtons/m^2 and a density on the order of 1400 kg/m^3. Consequently, due to its lower mass density, the use of kevlar composite allows the construction of higher energy density storage units. Most of the units in service, however, use steel wheels and are configured as homopolar generator/motor units. The energy stored in an inertial storage unit is given by

$$E = \frac{1}{2} I \omega^2$$

where I is the moment of inertia and involves the mass and geometry of the "flywheel" and ω is the angular velocity. Ultimately, the centrifugal forces cause the unit to fail. Factors of 2 are usually employed when setting a design limit for the peripheral speed of the wheel. Present systems typically operate at power levels less than 1MW, though sizes up to 1000 MW may be achievable.

Electrochemical Energy Storage

Batteries are probably the most traditional of the electrochemical energy storage devices. There are several categories of devices in current use. For the purposes of the SSP concept, secondary batteries (rechargeable) will be the only ones explored. The main attraction of this form of energy storage is that the efficiency is not limited to the Carnot cycle as thermal processes are. They are, in a sense, both energy storage and conversion devices. The output is electrical at some predesigned voltage and current. The electromotive force (EMF) is the difference between the electric potential of the electrodes. The terminal voltage equals the electromotive force minus the voltage drop in the battery due to its internal resistance. These parameters are rate limiting and tend to define the application regime for a particular battery technology. The proliferation of large centralized AC power systems and cheap energy limits large scale battery banks to standby power and DC auxiliaries. There are over 100 MW of battery power capacity currently installed throughout the National Power and PowerGen power companies in the United Kingdom. The battery market is still dominated by the lead-acid battery invented by Plante in 1859. It is relatively inexpensive and has proven reliability in the automotive and transportation industries. Specialty batteries on a somewhat larger scale have been built for automotive and space applications. Some of the newer lithium chemistries should also be included in future analyses for use in SSP systems.

A brief survey of capacitor technologies shows that the only type capable of serving as the intermediate store for a space solar power is the electrochemical versions based upon pseudocapacitance or the Chemical Double Layer (CDL). In 1887, Helmholtz discovered that the interface between a conductor and a liquid electrolyte formed a layer capable of storing charge. For strong electrolytes, this layer is estimated to be only a few angstroms thick. Due to the fact that there are materials with surface areas around two thousand square meters per gram, it is possible to produce practical capacitors with the surface area/interface thickness ratio on the order of the inverse of the permittivity of free space. This allows for the development of multi-farad capacitors in a reasonable size package. The state-of-the-art in battery and capacitor electrochemical energy storage systems is given in Table 2 below.

Table 2. Electrochemical Energy Storage Systems

Technology	Energy Density (W-hr/kg)	Power Density (W/kg)
Batteries	50-100	50-200
Capacitors	1-25	Up to 30,000

RECTENNA/PMAD INTERFACE ISSUES

Issues regarding the interfaces between the rectenna and a local energy storage system as well as between the rectenna and/or energy storage system and the utility power grid were discussed. Some of the key issues concerning the rectenna were identified and are included in the following list:

1. Overvoltage Protection of Many Parallelled Devices is Key.

2. Power Output Follows Power Input to First Order.

3. ~Output Voltage is Proportional to Load Resistance $^{1/2}$.

4. Underexcited Rectenna Elements in Parallel Have Small Drain.

5. Parallel Output Voltage Tends Toward Top Performers.

6. The Amount of Energy Storage in Rectennas is Very Small.

7. Current S-Band GaAs Rectennas Output ~28VDC/Element.

8. Diodes That Short Are Fused Open by Other Diodes Currents.

The various energy storage options considered in this study will receive energy from the rectenna array and then supply that energy to a ground-based electrical power grid when required. A power conditioning system (PCS) is required to interface the energy storage to the rectenna as well as to the electrical power grid. A rectenna capable of delivering hundreds of megawatts of power would be physically very large. The rectenna elements could be connected in various series and parallel configurations to produce a certain array output voltage and current. For the large power levels of this study, a high array output voltage would be desirable to reduce the size of cables needed to carry the current from the array to the energy storage. One possible PCS would be one high power DC-DC converter at the output of the rectenna. Another option would be to arrange the rectenna into various sub-arrays at a particular voltage and current level. A DC-DC converter could then be utilized with each sub-array. The DC-DC converter outputs

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could be connected either in series or parallel to produce a desired voltage and current. The resulting PCS would be a distributed system of DC-DC converters.

Several trade studies that should be performed for the power conditioning system (PCS) were identified. One trade-off study for the PCS would be to compare the different options for the interface between the rectenna and the energy storage unit. Possible PCS options to be considered are the merits of having one large high power unit at the output of the rectenna or having distributed dc-dc converters at a number of points along sub-arrays of the rectenna. The size (voltage, current, power) of each sub-element in a distributed power conditioning system and a practical number of such elements will be determined.

The interface between the energy storage element and the electrical power grid must be bi-directional in nature. An example of the type of PCS typically used with a particular energy storage system is the 12-pulse converter used as the interface between a SMES system and the grid. The SMES is charged from the electrical power grid in the rectifier mode. When energy is to be returned to the power grid, the converter changes to the inverter mode. This converter could not be utilized with a SMES supplied from a rectenna because of the DC voltage from the rectenna. One option is to have a PCS which has a single converter which is capable of charging the SMES with the DC voltage from the rectenna array and then supplying an AC voltage to the electrical power grid. Another option is to employ two different converters – one DC-DC converter to charge from the rectenna and another DC-AC converter for interface to the power grid. Both of these options assume one large energy storage device. Another trade study would be to evaluate distributed energy storage options. Previously, a distributed power system with DC-DC converters and sub-arrays were presented for the rectenna array. Each sub-array could also have its own energy storage. A distributed AC system could then be developed for interconnection to the power grid. Also, various PCS for the other types of energy storage systems must be evaluated. Issues specific to particular types of energy storage should be identified and included in the analysis for evaluating the different storage options.

Other parts of the PMAD system which were discussed included the method of transferring the power to the grid. In this context, superconducting wires were discussed for the transmission lines for the power system. It was acknowledged that several companies were actively pursuing this technology through research programs funded by other governmental agencies. It was felt

that the SSP system could capitalize on these research efforts and would likely have these types of cables available by the time a SSP system were implemented.

RECOMMENDATIONS

The recommendations resulting from this workshop was study some of the issues concerning the use of a terrestrial energy storage system in the Space Solar Power concept in more detail. The first task is to evaluate the current literature and assess the state-of-the-art for each of the energy storage options considered here. Included in these are compressed air energy storage (CAES), inertial energy storage (flywheels), superconducting magnetic energy storage (SMES), electrochemical storage (batteries and supercapacitors), and pumped hydro energy storage systems. Based upon this analysis, the potential of each of these systems for use in the space solar power system will be identified. The energy storage and power levels of each technology will be included in the analysis. Also, the scaling potential, life cycle, required infrastructure, site location, and cost will be used to compare the various technologies and to make recommendations as to which technologies should be investigated in more detail for possible implementation in the SSP system. Several trade studies should be performed for the power conditioning system (PCS). One trade-off study to be included for the PCS would be to compare the different options for the interface between the rectenna and the energy storage unit. Possible PCS options to be considered are the merits of having one large high power unit at the output of the rectenna or having distributed dc-dc converters at a number of points along sub-arrays of the rectenna. The size (voltage, current, power) of each sub-element in a distributed power conditioning system and a practical number of such elements will be determined.

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DC-DC converter to charge from the solar array and another DC-AC converter for interface to the power grid. Both of these options assume one large energy storage device. Another part of this study would be to evaluate distributed energy storage options. Previously, a distributed power system with DC-DC converters and sub-arrays were presented for the solar array. Each sub-array could also have its own energy storage. A distributed AC system could then be developed for interconnection to the power grid. Also, various PCS for the other types of energy storage systems will be evaluated. Issues specific to a particular type of energy storage will be identified and included in the analysis for evaluating the different storage options.

As a result of this workshop, it is recommended that an additional workshop on terrestrial energy storage systems and ground systems for Space Solar Power Systems be conducted to address the issues that were identified in this initial workshop. The power conditioning system used to interface the rectenna array to the local power grid or an energy storage system needs additional study to determine the most efficient means to transfer the energy received by the rectenna to a useful format for delivery to the power grid. A second workshop would enable more involvement from the utility companies to get their input as to how the SSP system should be tied to the power grid. Also, representatives for companies developing the various energy storage options being considered would be available to provide detail on the level of development required to operate at the levels required for the SSP system.

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April 27, 2000

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Subject: Final Report   NASA NAG8-1563

Dear Sir:

Enclosed herewith you will find an original copy of the final report on research project entitled "Terrestrial Energy Storage SPS Systems".

Should you have questions, please contact me direct at (334) 844-5907.

Sincerely,

Mickie Jacob
Contracts & Grants Specialist

Cc: Ms. Valerie Holmes, Grants Officer
        Joe Howell / PS05, Technical Officer
        NASA Center for Aerospace Information, Maryland
        AU Office of Sponsored Programs

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