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A TECHNICAL OVERVIEW OF THE "SUNTOWER" SOLAR POWER SATELLITE CONCEPT†

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Abstract—During 1995–1996, the National Aeronautics and Space Administration (NASA) conducted a far-reaching reexamination of the technologies, systems concepts and terrestrial markets that might be involved in future space solar power (SSP) systems. The principal objective of this "fresh look" study was to determine whether a solar power satellite (SPS) and associated systems could be defined that could deliver energy into terrestrial electrical power grids at prices equal to or below ground alternatives in a variety of markets, do so without major environmental drawbacks, and which could be developed at a fraction of the initial investment projected for the SPS Reference System of the late 1970s.

One of the key concepts emerging from the "fresh look" SSP study is the "SunTower" SPS system. This concept exploits a variety of innovative technologies and design approaches to achieve a potential breakthrough in establishing the technical and programmatic feasibility on initial commercial SSP operations. Capable of being deployed to either low Earth orbit or middle Earth orbit altitudes and various inclinations, the SunTower concept involves essentially no in-space infrastructure and requires no unique heavy lift launch vehicle. The concept, which can provide power to global market places appears to allow up to a factor of 30:1 reduction in initial investment requirements, compared to the 1979 SPS Reference Concept. This paper presents a technical overview of the SunTower SPS concept, including key technologies, sensitivity trades, operational scenarios. Potential non-SPS space program uses of the SunTower concept and related technologies are identified, including human exploration, space science and commercial space applications. Published by Elsevier Science Ltd

1. INTRODUCTION‡

The concept of generating solar power in space for use in terrestrial markets on Earth was introduced by Dr. Peter Glaser in 1968. This idea — solar power satellites (SPS) — has captured the imagination of many visionaries around the world during the intervening decades. However, the technological implementation of this elegant concept is far from trivial. It depends on a wide variety of technical advances, and is enabled by the technology of wireless power transmission (WPT). As an illustration of this fact, Fig. 1 depicts the challenges associated with WPT for a generic case. Still, significant advances in many key areas for WPT and solar power generation were made during the 1960s.

As a result, major SPS systems definition study efforts conducted in the US in the 1970s. Unfortunately, these studies yielded a system implementation approach (the "1979 SPS reference System") that required an investment of more than $250B (US$,'96). Figure 2 provides an illustration of some of the major system elements of the 1970s system approach. Because of the high projected initial investment and other factors, all serious work on space solar power (SSP) in the US stopped around 1980.

During 1995–1996, the National Aeronautics and Space Administration (NASA) conducted a far-reaching reexamination of the systems concepts, technologies and terrestrial markets that might be involved in future space solar power

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‡A glossary of acronyms is given in Appendix at end of paper.

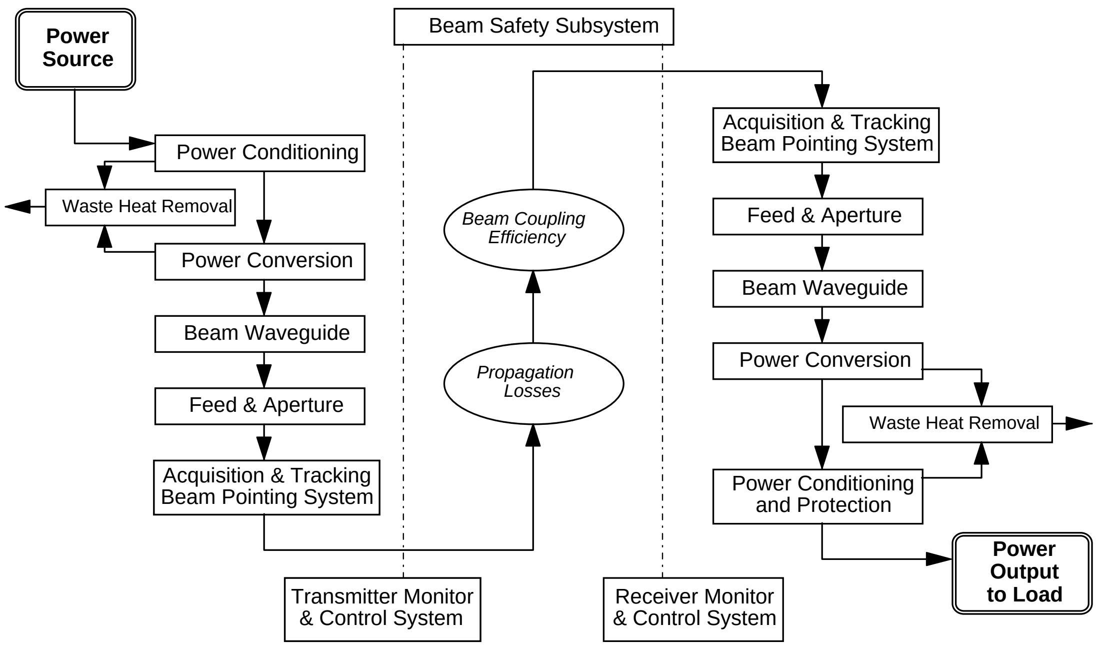

Fig. 1. Generic diagram of technical challenges associated with wireless power transmission.

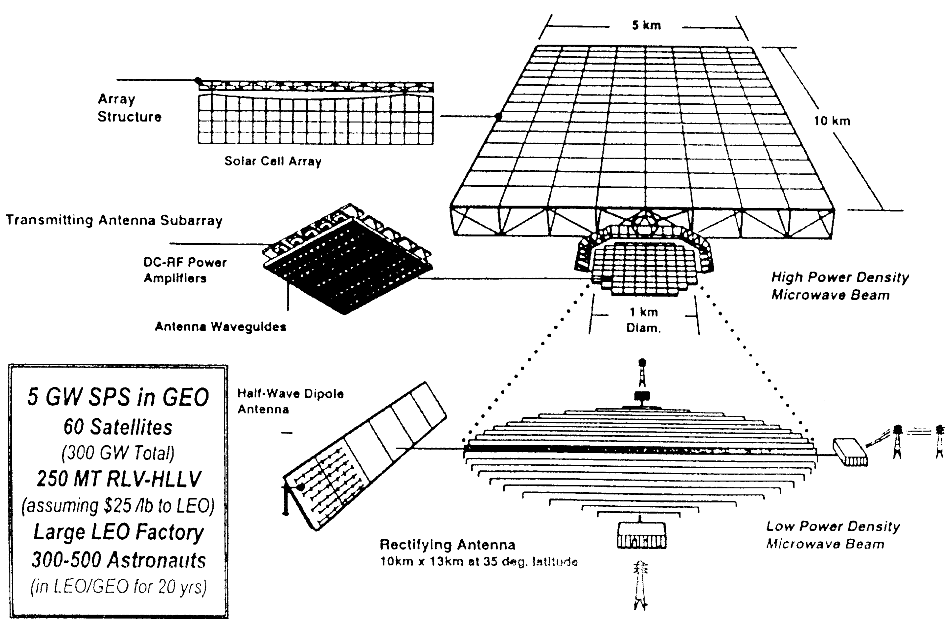

Fig. 2. 1979 SPS Reference System Concept: 5 GW power output, geostationary Earth orbit-based systems.

systems.† The principal objective of this "fresh look" study was to determine whether an SPS and associated systems could be defined that could deliver energy into terrestrial electrical power grids at prices equal to or below ground alternatives in a variety of markets, do so without major environmental drawbacks, and which could be developed at a fraction of the initial investment projected for the 1979 SPS Reference System.

One of the key concepts emerging from the "fresh look" SSP study is the "SunTower" SPS system. This concept exploits a variety of innovative technologies and design approaches to achieve a potential breakthrough in establishing

†The overall NASA study is the subject of a companion paper, "A Fresh Look at Space Solar Power: New Architectures, Concepts and Technologies" IAF-97-R.2.03.

the technical and programmatic feasibility on initial commercial SSP operations. Capable of being deployed to either low Earth orbit (LEO) or middle Earth orbit (MEO) altitudes and various inclinations, the SunTower concept involves essentially no in-space infrastructure and requires no unique heavy lift launch vehicle (HLLV). The concept, which can provide power to global market places appears to allow up to a factor of 30 : 1 reduction in initial investment requirements, compared to the 1979 SPS Reference Concept. In addition, a number of potential non-SPS space program uses of the SunTower concept and related technologies have been identified, including human exploration, space science and commercial space applications.

2. TECHNICAL STRATEGIES

Several technical strategies were woven together to create the fabric of the SunTower concept. The following paragraphs briefly summarize some of the design choices that drove the cost of the 1979 SPS Reference System and characterize the new technical strategies developed in the "fresh look" study as ways to reduce the costs in new system concepts.

2.1. Earth-to-orbit transportation

All space industrialization concepts are constrained or enabled by projected advances in Earth-to-orbit transportation — including SSP.

2.1.1. The 1979 SPS Reference System. One of the major initial investments that drove the projected cost of the 1979 SPS Reference System was that required to create a very large-scale, reusable launch vehicle system. This HLLV system, relied on a two-stage-to-orbit (TSTO) approach and was planned to launch approximately 250 Mt of payload into a low Earth orbit. The gross liftoff weight (GLOW) of these systems was estimated to be as high as 11, 000 Mt. The facilities required to support these enormous HLLVs were extremely large as well and entailed extensive operations and maintenance (O& M). Nevertheless, the ETO cost per kilogram of payload for these launch systems was projected at an exceptionally — and almost certainly unrealistically — low figure: about \$50–\$100/kg. A more credible estimate for the recurring cost per kilogram of payload of a first generation, 99% reusable single-stage-to-orbit (SSTO) vehicle has been estimated to be about \$2000/kg (Access to Space, Option III, 1994).

2.1.2. The SunTower. In order to avoid the enormous initial expense of developing an large, SPS-unique HLLV-driven launch infrastructure, a fundamental technical strategy of the "Fresh Look" study was to seek concepts that might be launched without the use of an HLLV. The SunTower system concept (described in more detailed in the following sections) involved the assembly of four major types of system elements: (1) the transmitting phased array, (2) the solar power arrays, (3) the power "backbone" and its interconnections and associated propulsion modules, and (4) other miscellaneous system elements. Each of these can, it appears, be launched in pre-packaged elements of less than 10–20 Mt in size. Launching SSP elements in these payload class was viewed as especially important because the launch systems to do the job would not be unique to SPS.

Previous studies, and in particular the 1993–1994 Commercial Space Transportation Study (CSTS) strongly suggested that major new space industries could be induced if the cost of space access for payloads in the 20 Mt class could be driven below about \$1000/kg of payload. Recent studies, in particular the highly reusable space transportation (HRST) study suggest that it is possible to achieve recurring costs in space launch of approximately \$400/kg of payload or less through the use of one or more innovative systems concepts and new technologies. Some of these are summarized in the paragraphs which follow.†

2.1.3. In-space infrastructure. The desire to avoid the use of an HLLV system for ETO transport leads in turn to a major SSP technical strategy: modularization of SPS systems. However, exceptionally large, compression-stabilized structural concepts require either: (a) very elaborate kinetically deployed mechanical elements, or (b) separate facilities, equipment and/or personnel to perform assembly of the structure. The former can involve unacceptably high levels of risk due to the complexities of such systems in deployment. The latter however, may require high initial investments.

2.1.4. The 1979 SPS Reference System. The Reference System relied exclusively on compression-stabilized structures which were assembled at large, stand-alone facilities in LEO and GEO. For example the primary solar array of the 1979 system was

†These concepts are discussed in some detail in IAF-97-V.3.06, "Highly Reusable Space Transportation: Advanced Concepts and the Opending of the Space Frontier".

a 5 km × 10 km × 0.5 km truss-structure platform. One of the principal cost drivers associated with the 1979 SPS Reference System was the requirement for large-scale in-space "factories" at which the 60 SPS in the constellation would be assembled. Modularization entailed another design opportunity: elimination of infrastructure in space.

2.1.5. The SunTower. A central design strategy that was formulated early in the "fresh look" study was to pursue tenaciously the goal of eliminating costly initial in-space infrastructure associated with the manufacture/assembly of SPS in LEO and GEO. This design strategy was manifested strongly in the SunTower SPS concept.

However, as noted above, heavy reliance on kinematically deployed mechanical systems was viewed as inconsistent with overall design goals associated with high packaging efficiency and good reliability in deployment. As a result, tension-stabilized structures were examined. Two basic types of tension-stabilized structures were employed in the SunTower concept: (1) the use of a gravity-gradient stabilized tether-backbone for the primary "trunk" of the SPS system, and (2) the use of inflatable structures in individual concentrator-photovoltaic solar array elements.

2.1.6. Manufacturing and the economies of scale. Clearly, in order to succeed economically, all of the major system elements of an SPS must be capable of being manufactured drastically less expensively that any current spacecraft or space power system. If one is building scores of SPS platforms, the answer can reasonably be expected to be "yes". However, a central issue for SSP systems concepts is: can the *first* platform be manufactured cheaply?

2.1.7. The 1979 SPS Reference System. In the case of the Reference System, the major system elements were — although very aggressive technologically — largely consistent with these goals. Even from the first platform, most system elements were manufactured in extremely large lot sizes (1000s to 100,000s of units) and could be expected to be affordable. However, several major system elements were not modularized — for example the unique, 200–300 m diameter mechanical gymbol that connected the phased array to the solar array. Moreover, the systems associated with the in-space infrastructure for SSP system assembly and construction were not planned to be manufactured in anything approaching the quantities envisioned for the platforms themselves. For example, modules for astronauts would have been built in lot sizes of 10s–20s, extravehicular activity systems in lot sizes of 100s, etc. Hence, although the majority of the mass could be projected to be very low cost ($500–$1000/kg), major elements could be expected to be drastically more expensive (perhaps ($5000–$20,000/kg)

2.1.8. The SunTower. As noted previously, the "fresh look" study drove toward the elimination of major in-space infrastructure, including a reliance on astronauts for SPS assembly and construction. At the same time, to allow launch on smaller ETO systems, the building blocks of the new SPS concepts were designed to be highly modular — thus supporting incidentally the goal of low cost manufacturing. Several other detailed elements of the SunTower concept support this strategic design goal, including the use of modular solar arrays and that of either solid state or magnetron devices for RF power generation (rather than much large single electron tube devices (e.g. klystrons).

3. THE SUNTOWER SYSTEM CONCEPT

The SunTower SPS can be described as a modular, gravity-gradient stabilized system concept in which power is generated in a series of identical advanced photovoltaic (PV) arrays along a power-transmitting "backbone" which conveys the power generated to a nadir-pointing phased array at the base of the "tower". Figure 3 provides a summary diagram of the SunTower concept. The following paragraphs summarize the main features of the concept.

3.1. Architectural options

3.1.1. Orbits. The SunTower system concept (with some variations) may be deployed into any one of several specific orbits, including: (1) a sun-synchronous (SS) LEO, (2) an MEO, with any one of several potential orbital inclinations, and (3) geostationary Earth orbit (GEO). Three cases have been examined to date, with specific orbits. These are: LEO-SS at an altitude of 1500 km, low MEO at an altitude of 6000 km and high MEO at an altitude of 12,000 km.† In particular, for the MEO options, the two sub-cases that have been defined have involved: (a) a constellation of approximately 24 satellites, placed in families of four in each of six orbital planes, and (b) a constellation of as few as six or as many as 30 satellites, placed evenly spaced in a common equatorial orbit.

†The first two cases (LEO-SS and low MEO) are documented in the April 1997 "Fresh Look" study report.

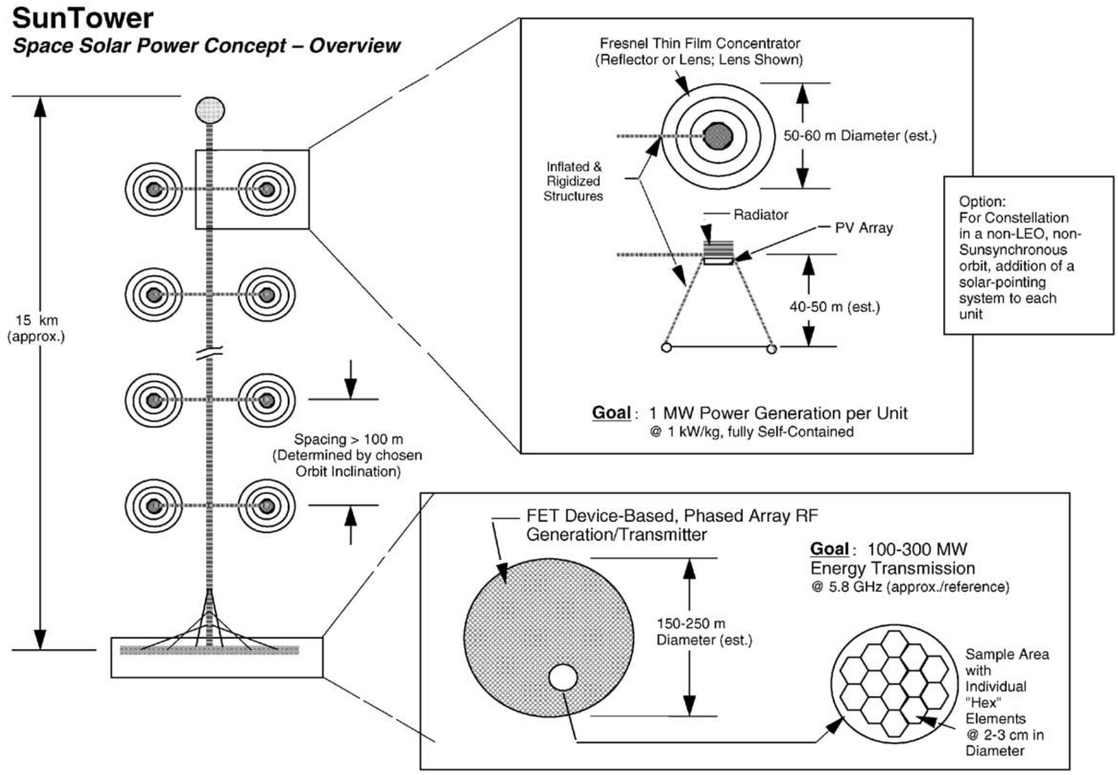

Fig. 3. The “SunTower” solar power satellite system concept.

3.1.2. Space transportation. The SunTower system depends upon launch to LEO at costs of less than \$200–\$400/kg of payload. The ongoing Reusable Launch Vehicle (RLV) program has as a near-term goal the demonstration of technologies needed to enable launch to LEO at costs of less than \$2000/kg of payload. This capability would be established using either an SSTO or a TSTO all-rocket vehicle using cryogenically cooled liquid oxygen (LOX) and liquid hydrogen as propellants.

The ongoing HRST study project (1995–1997) has defined a variety of technical approaches that hold promise for dramatically reducing the cost of ETO transportation. However, achieving truly dramatic reductions in launch costs are enabling for SSP. Figure 4 illustrates the sensitivity of the potential internal rate of return (IRR) of a notional MEO SunTower constellation to variations in the launch price. Although returns remain positive to relatively high launch prices, it is clear that launch costs of below \$400/kg must be the goal if SSP systems are to be economically viable.

3.1.3. In-space assembly, maintenance and operability. As discussed above, the elements of the SunTower are projected to be self-assembling — i.e., capable of individual rendezvous and attachment to the “growing” space platform. In addition, the system elements of the SPS must be capable of extended duration operations in the space environment without major maintenance operations. In addition, the system concepts must be designed such that when maintenance or repair is required, it can be carried out quickly and effectively to return the SPS to service as quickly as possible. Assuming that at a major refurbishment involves replacing about 10% of the mass of the SunTower SPS, Fig. 5 indicates the sensitivity of the potential IRR of a notional MEO SunTower constellation to variations in the time between such maintenance operations. Returns remain strong as long as this duration does not fall below about 10 years.

3.1.4. Power generation. In the area of power generation, the basic design/technology goals that must be met to make the SunTower system concept viable are that the power per unit mass should be 500–1000 W/kg, and that the cost per unit power should be less than \$1–2 W^{-1}. The selected approach for the SunTower was to utilize two rapidly maturing technologies: thin film structures (optical systems) in combination with multiple band gap PV arrays. As indicated in Fig. 3, one system design examined involved the use of a large Fresnel

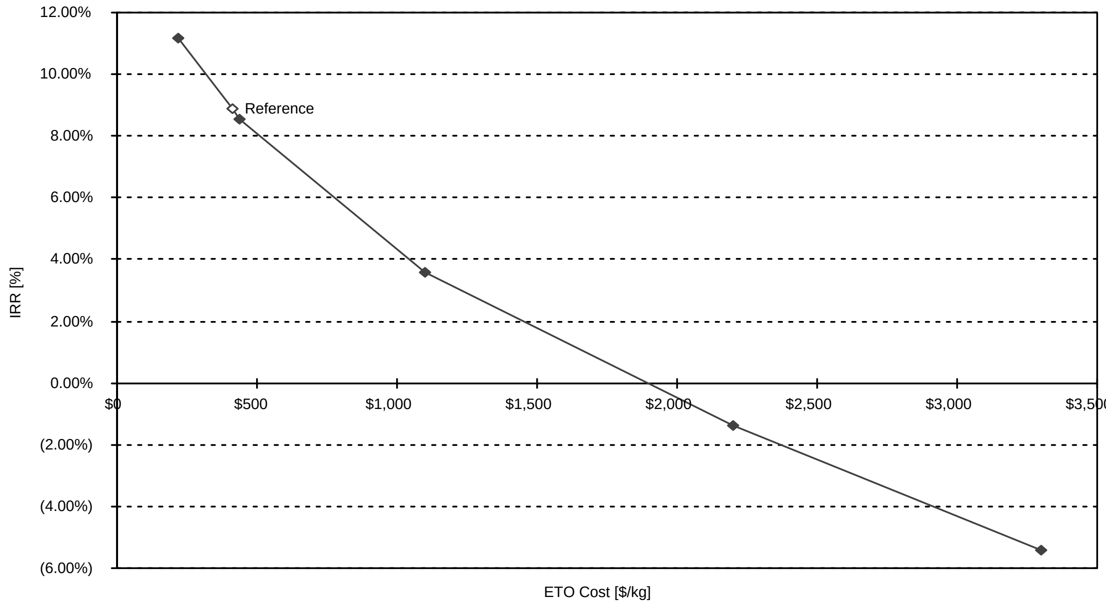

Fig. 4. Sensitivity of a typical MEO "SunTower" SPS scenario to variations in ETO costs.

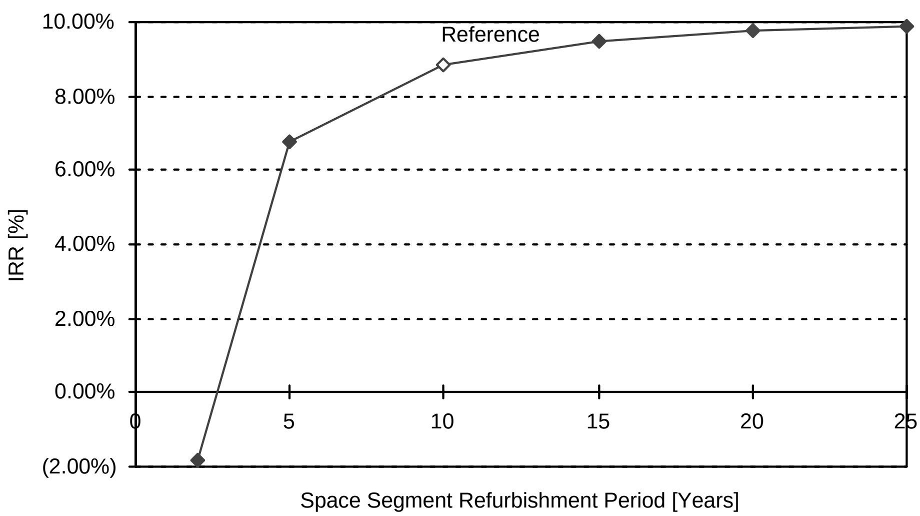

Fig. 5. Sensitivity of a typical MEO "SunTower" SPS scenario to variations in the lifetime before system refurbishment.

concentrator. However, unlike terrestrial or typical space applications of this technology, the approach examined here was to limit the concentration ratio to that which could be supported by fully passive cooling at the PV array (with the goal of reducing system mass). Figure 6 illustrates the sensitivity of the potential IRR of a notional MEO SunTower constellation to variations in the specific mass (kg/kW) of the PV array. Although returns remain good below 1 kW/kg, specific masses of better than 0.5 kW/kg must be the goal if SSP systems are to be economically viable.

3.1.5. Platform power management and distribution (PMAD) systems. The SunTower PMAD system includes a variety of new elements. For example, a high temperature superconductivity (HTSC) power "backbone" is used to convey power from the PV arrays to the RF phased array, including cabling, support structure. Additional support equipment involves active refrigeration systems, tubing, multilayer insulation, and radiators. In addition, power cabling interconnects at each of the solar PV nodes are needed to accommodate docking and/or automated "plug-in" of modular units (e.g., PV

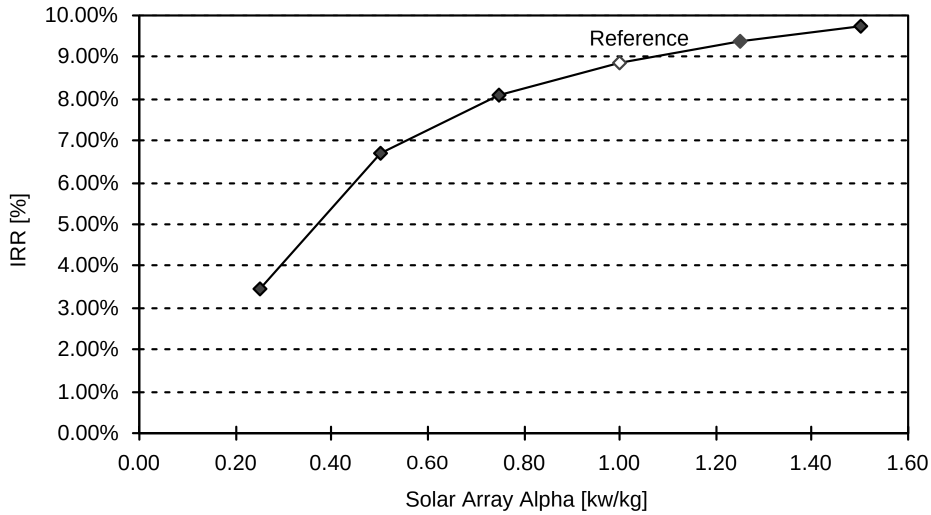

Fig. 6. Sensitivity of a typical MEO "SunTower" SPS scenario to specific mass variations in the PV array.

collector pairs). Also, for the RF system, a planar array power harness is needed, including interconnections between the HTSC power backbone and the RF transmitter array, buses between power conditioning circuitry and the transmitting devices, and harness support structure.

Advanced power conditioning is required, including DC/DC conversion, switching and protection circuitry, and energy storage if used. Also, the PMAD system may encompass the reference phase distribution system which includes receiver(s) and other components needed to capture reference signals from ground sites and distribute them to the transmitter sub-arrays.

3.1.6. Power transmission. The approach to WPT used in the 1979 SPS Reference System was the use of about 70,000 klystron electron tubes (each generating about 100 kW) which fed a single, mechanically rigid waveguide structure. The resultant array was mechanically pointed using a very large gymbol. Recently, the far-simpler concept of using a larger number of Magnetron electron tubes (each generating up to about 3 kW) has matured. In the SunTower system concept, a basic design feature was the use of electronic beam-steering to guide the generated RF beam rather than mechanical pointing. Also, a frequency of 5.8 GHz was analyzed for use in WPT.

3.1.7. Terrestrial systems. All cases of SunTower examined thus far utilize RF WPT at 5.8 GHz (as noted above), with the beam generation performed by a solid state device-based array. A rectifying-antenna ("rectenna") is assumed to be the common, primary power receiver and link to terrestrial power distribution systems. In addition, a moderate-scale terrestrial energy storage system should be included to assure continuous power availability (perhaps at a somewhat reduced level), even during the early years of constellation deployment.

3.1.8. LEO-SS case. The lowest cost-to-first-power SunTower option that has been identified is that of a constellation in an SS LEO, inclined at an angle of about 95° and at an altitude of about 1500 km. It this case, the individual SPS do not require far-ranging sun-pointing capabilities for their solar arrays — thus reducing costs and complexity. Moreover, because of the short distance the total power output and associated size of the transmitting RF phased array can be minimized for a receiving rectenna of a particular size. For this architecture, the SunTower system defined was defined to produce about 50 MW on the ground. (This represents a factor of 100:1 reduction below the power output of the 1979 SPS Reference System.) By using a much lower power level, the overall mass of the SPS was reduced to TBD MT.

However, a particular SPS in this orbit can serve individual sites on the ground only during a relatively short period of time around local dawn and dusk. In order to achieve the maximum coverage, $\pm 30^\circ$ electronic beam steering capability was planned, and a "formation" of 18 SPS was assumed. Such a formation could provide continuous power on the ground for about 1 h.

Even with $\pm 30^\circ$ electronic beam steering capability, each SPS in an LEO can address a particular site on the ground for only a very few minutes In order to achieve better utilization of SPS space assets, higher orbits must be considered.

3.1.9. MEO SunTower case 1 : 6000 km (30° *inclination orbits*). By placing SunTower SPS in a higher MEO, a constellation of satellites can provide nearly continuous power to specific sites on the ground. The case examined in the "fresh look" study involved placing a minimum of 21 SunTower SPS in a family of 6000 km MEO inclined at angles of 30°. These SunTower SPS — which were projected to require ±30° electronic beam steering capability — were capable of providing near-continuous power to sites on the ground between 60° north latitude and 60° south latitude. Each of these satellites was sized to produce an average power output of 250 MW power on the ground. The mass of each platform was about TBD Mt.

However, SPS in this orbit — which is just past the most intense region of the Earth's Van Allen radiation belts at about 5000 km — would require dramatic advances in radiation hardening for all systems. Solar arrays, in particular have been found to be susceptible to degradation due to exposure to radiation.

3.1.10. MEO SunTower case 2 : 12, 000 km (*common equatorial orbit*). This architecture represents a modest modification of the MEO case described above. In particular, at this altitude, the RF electronic beam steering goal (and hence the phase-shifter requirements and costs) can be substantially relaxed. A beam steering capability of only ±15° provides the same area of ground track coverage as was achieved in the preceding case (at 6000 km altitude). Although the range of sites that can be addressed on the ground is reduced for this case, it has the advantage that with a given number of satellites (e.g., 18 as used before), power beam transmission can be restricted to a tighter range of angles around local vertical at the ground receiver. As a result, a higher end-to-end WPT efficiency can be achieved.

This architecture does involve an inherent, periodic shadowing of the SPS by the Earth when it is at local midnight and of the arrays by themselves at local noon — hence necessitating the installation of a relatively modest energy storage system at the ground site. This requirement is not expected by be substantial (although detailed analyses have not yet been conducted). For example, if the shadowing occurs for a duration of about 30 min and the SPS delivers an average of 400 MW on the ground, then the energy storage system must be sized to provide approximately 2×10^5 kW h (or about 7×10^{11} J) of storage.†

The MEO SunTower equatorial architecture (at 12, 000 km) has an additional advantage during the early years of constellation construction. In particular, a single satellite can be planned to revisit a particular target rectenna on the ground for about 10 min or more approximately once every 6 h. Unlike the inclined orbit case, this approach could enable earlier, longer duration power services from the completion of the first satellite. Cases that combine an early MEO equatorial deployment with later MEO inclined orbit deployment could be attractive.

4. SSP TECHNOLOGIES

Very low cost space launch, discussed above, is clearly required to even contemplate SSP. However, diverse advances are vitally needed in various other technology areas to enable the SunTower concept. These include the following:

- Low-cost, low specific-mass PV solar arrays (including thin film and concentrator arrays, and multi-bandgap PV systems),
- Low-mass and low-cost RF beam generation, including high-efficiency solid state power amplifiers and ultra-low cost microwave phase shifters,
- Low-cost, low specific-mass thermal management systems,
- High-performance, high-specific impulse electric propulsion systems,
- Systems that respond robustly to the impact of debris or micro-meteorites,
- HTSC power cabling,
- Hoyt tether-based power cabling configurations,
- Long-lived, ultra highly reliable cryogenic coolers,
- Autonomously deployable power system networks with multiple redundant interconnections,
- Low-mass, long-lived DC/DC power conversion systems,
- Real-time autonomous power system network reconfigurability,
- Integrated non-destruction inspection/evaluation,

†This compares well to a comparable ground-based baseload solar power system of the same size which could require an energy storage system of up to 5×10^7 kW h (or about 1.7×10^{14} J).

- Various appropriate materials (insulations, radiators, etc.),
- Self-deploying electromechanical interfaces,
- High-efficiency, all-weather, rectenna systems (@ 2.45 GHz and 5.8 GHz),
- Various appropriate materials (composite structures, insulators, radiators, etc.),
- Robotic repair/maintenance/adjustment,
- Others.

5. SUMMARY

The global demand for clean, safe renewable energy continues to grows rapidly. The principal barriers to the development and deployment of SPS to help meet this demand are three-fold: political, technical and economical. Although GEO-based SPS — in part because of their potential for very high utilization of capacity — have the potential to achieve the highest financial returns, these systems also involve the highest initial investments. As a consequence, they are unlike to be the first large space power systems constructed.

Relatively small SPS in lower orbits, such as the LEO-SS and MEO SunTower systems concepts described above may be deployable at substantially lower initial costs that larger GEO concepts. Although many technologies must be advanced first, systems of this type may enable commercial space solar power generation to begin early in the next century.

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APPENDIX

Glossary of acronyms

DOE	Department of energy
EM	Electromagnetic
FEL	Free-electron laser
GEO	Geostationary Earth orbit
GHz	Gigahertz
GW	Gigawatts
HRST	Highly reusable space transportation
JPL	Jet propulsion laboratory
JSC	(NASA) Johnson Space Center
kW	Kilowatts
LANTR	LOX-augmented nuclear thermal rocket
LEO	Low Earth orbit
LeRC	Lewis Research Center
LOX	Liquid oxygen
LUNOX	Lunar oxygen
MEO	Middle Earth orbit
MSFC	(NASA) Marshall Space Flight Center
MW	Megawatts
NASA	National Aeronautics and Space Administration
NTR	Nuclear thermal rocket
OECD	Organization for Economic Cooperation and Development
PV	Photovoltaic
RBCC	Rocket-based combined cycle (Propulsion)
RF	Radio frequency
SEPS	Solar electric propulsion system
SPS	Solar power satellites
SSP	Space solar power
W	Watts
WPT	Wireless power transmission