A Fresh Look at Space Solar Power: New Architectures, Concepts and Technologies

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ABSTRACT

The concept of generating solar power in space for wireless transmission to receivers on the ground has been discussed at some length during the past three decades. During the first decades of the new century, global demand for electrical power is projected to grow dramatically - perhaps doubling from 12 terawatts to more than 24 terawatts. Achieving this power growth while managing environmental impacts effectively is a cruical international challenge. During 1995-1996, the National Aeronautics and Space Administration (NASA) conducted a far-reaching re-examination 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.

Working with a major focus on emerging nations - the study examined 5 different markets and about 30 different SPS concepts, ranging from the 1979 SPS Reference Concept defined by the US Department of Energy and NASA to very advanced concepts involving technologies that have not yet been validated in the laboratory. Following a preliminary assessment of technical and economic risks and projected costs, 7 SSP system architectures and 4 specific SPS concepts were chosen for employing in greater depth using a comprehensive, end-to-end systems analysis employing a desktop computer modeling tool that was developed for the study. Several innovative concepts were defined and a variety of new technology applications considered. A key ground rule to achieve initial cost goals was to avoid wherever possible the design, development, test and evaluation costs associated with SSP-unique infrastructure. Three architectures in particular were identified as promising: a sunsynchronous low Earth orbit (LEO) constellation, a middle Earth orbit (MEO) multiple-inclination constellation, and one or more stand-alone geostationary Earth orbit (GEO) SPS serving single, dedicated ground sites. This paper presents a summary of the results of the "Fresh Look" study, including architectures, systems concepts and technologies.

INTRODUCTION

During 1995-1997, the National Aeronautics and Space Administration (NASA) conducted a far-reaching, preliminary 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.

Approximately 100 experts in a wide variety of disciplines participated in this two-year study, which involved three major workshops. Working within the context of the global energy marketplace of the 21st Century - including a major focus on emerging nations - the study examined 5 different markets and about 30 different SPS concepts, ranging from the 1979 SPS Reference Concept defined by the US Department of Energy and NASA to very advanced concepts involving technologies which have not yet been validated in the laboratory.

Following a preliminary assessment of technical and economic risks and projected costs, 7 SSP system architectures and 4 specific SPS concepts were chosen for examination in greater depth using a comprehensive, end-to-end systems analysis employing a desk-top computer modeling tool that was developed for the study. Several innovative concepts were defined and a variety of new technology applications considered, including solid state microwave transmitters, extremely large tension-stabilized structures (both tethers and inflatable structures), and autonomously, self-assembling systems using advanced in-space computing systems. A key strategy to achieve initial cost goals was to avoid wherever possible the design, development, test and evaluation costs associated with SSP-unique infrastructure, such as fully reusable, heavy lift launch vehicles.

Three architectures in particular were identified as promising: a sun-synchronous low Earth orbit (LEO) constellation, a middle Earth orbit (MEO) multiple-inclination constellation, and one or more stand-alone geostationary Earth orbit (GEO) SPS serving single, dedicated ground sites.

This paper presents a strategic summary of the results of the "Fresh Look" Study, including architectures, systems concepts and technologies. It also provides a summary of the very promising results that emerged from preliminary market and economic analyses that were conducted.

1976-1 980 with support from NASA. This study resulted in the 1979 Reference SPS System, shown in **Figure 1**.
All solar power concepts - space-based or terrestrial - inherently require large areas. Since the sun provides about 1365 watts per square meter of energy at the Earth's orbit, generating a megawatt with a 20% efficient array requires an area of about 3700 square meters. However, the SPS concept that emerged by 1979 was not only large, it was also infrastructure-rich because it was based upon the large, astronaut-erected space platform concepts that

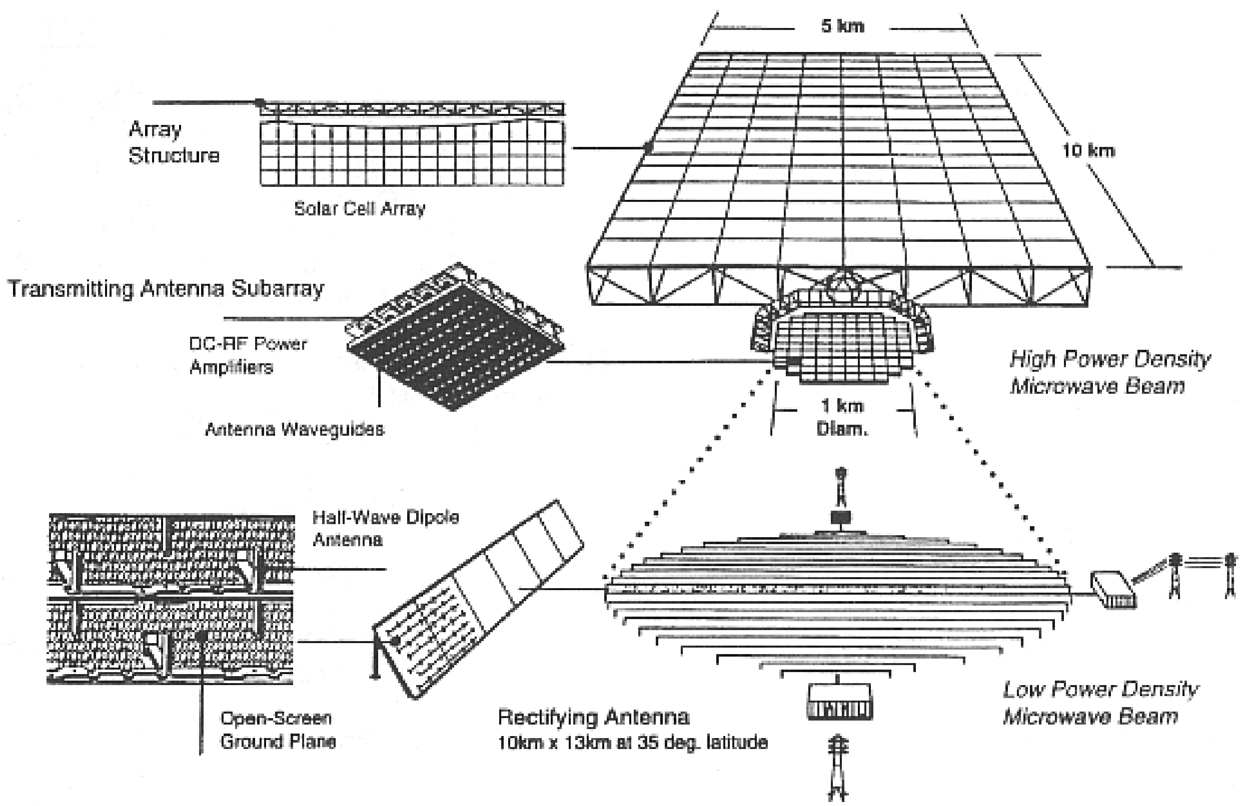


Figure 1: 1979 Reference System Concept:

were common of this era in which Gerard O'Neil and others envisioned the eventual construction of vast, artificial cities in space.

THE 1970s DOE-NASA SPS STUDY

The concept of generating power from sunlight in space, and then transmitting that power by wireless means to the surface of the Earth for use, was first invented by Dr. Peter Glaser of Arthur D. Little. Various studies of this concept were conducted during the 1970s, culminating in a major study led by the US Department of Energy (DOE) in

The 1979 SPS architecture entailed deploying a series of as many as 60 SPS into geostationary Earth orbit (GEO). Each of these SPS was planned to provide dedicated, baseload power ranging from 5 to 10 GW of continuous energy for a "megacity" on the Earth - quite probably a city in the U.S. itself.

An enormous single platform, assembled in space from large, compression-stabilized struts and joints was the fundamental building block of this concept. On the large SPS platforms - which ranged from 5 km by 10 km in area and 0.5 km deep for a system delivering 5 GW - a host of very large discrete system elements would be assembled to provide three major functions: power collection and management (including PV arrays, thermal management, etc.), platform support systems (such as control systems to provide three-axis stabilization, and so on) and RF power generation and transmission.

The 1979 SPS Reference platforms, comprised as they would have been of large, erected structures and installed systems, were envisioned to be deployed through the use of a massive, unique infrastructure. This infrastructure included a fully-reusable two-stage-to-orbit (TSTO) Earth-to-orbit (ETO) transportation system as well as a massive construction facility in low Earth orbit (LEO) that would have required hundreds of astronauts to work continuously in space for several decades. The financial impact of this deployment scheme was significant: more than $250 billion (in 1996 dollars) was estimated to be required before the first commercial kilowatt-hour could be delivered.

Ultimately, the US National Research Council (NRC) and the (former) Congressional Office of Technology Assessment (OTA) concluded following reviews in 1980-1981 that although solar power satellites were technically feasible, they were - based on the 1979 SPS Reference - programmatically and economically unachievable. Although the NRC recommended that related research continue and that the issue of SSP viability should be revisited in about a decade, in fact all serious effort on solar power from space by the U.S. government ceased.

WHAT HAS CHANGED?

There have been a number of important changes in the external context for consideration of space solar power during the past 15-20 years. The most important is the increasing demand for energy globally and the resulting increasing concern regarding carbon combustion, CO2 emissions and global climate change, discussed below. As a result, there is a major priority being place on the development of renewable energy sources.

Another important change has occurred at the US national policy level. US National Space Policy now calls for NASA to make significant investments in technology (not a particular vehicle) to drive the costs of ETO transportation down dramatically. This is, of course, an absolute requirement of space solar power. This policy is, of course, independent of any SSP-related considerations and thus need not be "charged" against the cost of developing SSP technology. Also, a variety of other key technical advances have been made involving many key technological areas and diverse new systems concepts. Although systems-level validation of key technologies, such as power conversion and large-scale wireless power transmission (WPT) have not occurred, component-level progress has been great.

There are fundamentally new opportunities for partnerships compared to the environment of 20 years ago. Strong opportunities exist now for international teaming and resultant support. Recently, SSP activities have occurred in Japan, Canada, Europe, Russia. For example, the Japanese have conducted a wide variety of experiments, studies and technological research related to space solar power during the past 10 years, including a particular SSP study entitled: "SPS 2000".

Finally, there is a new paradigm for the relationship between governments and industries, for example with NASA's role in research and development to reduce risk and to seek government mission applications -but not to actually develop operational systems.

As a result of these and other factors, in 1995 NASA's Advanced Concepts Office determined that the time was appropriate to revisit the subject of space solar power.

THE NASA "FRESH LOOK" STUDY

The Market

The global energy marketplace is very dynamic. World population is increasing by about 80 million each year. The multinational "middle class" is growing still more quickly. The US Department of Energy (DOE) Energy Information Agency (EIA) has projected that the world-wide use of energy will approximately double in the next twenty years - and that it will about double again in the twenty years that follow. These projections are founded on the ongoing growth in populations in the developing world and simultaneous growth in the per capita consumption of power in those nations. **Figure 2** illustrates the projected international marketplace for electrical energy during the next 20 years.

Another forecast has also been made. The International Program on Climate Change (IPCC) and the US Global Change Research Program (USGCRP) in their most recent annual report recount strong evidence that the Earth's temperature has increased by at least 0.5-1.0 degrees Fahrenheit during the past century. The cause of this increase is a subject for considerable discussion. However, it is believed by more than 2400 scientists that this increase is the result of human activities - predominantly the unprecedented use during the 20th century of oil, coal and natural gas (fossil fuels) for transportation and energy production.

Fundamentally, the global demand for energy is increasing due to population growth at the same time that it per capita energy use is growing - driven by the equally strong economic growth being experienced in many developing nations. Fossil fuel combustion-based power plants remain the dominant choice to meet energy demand. As a result, it is expected by the IPCC that increased power production will lead to accelerating increases in the level of so-called "greenhouse gases" (predominantly carbon dioxide).

Conversely, the US domestic energy marketplace is relatively saturated, both with power plants and power distribution systems. Greater gains in power "production" and greenhouse gas reductions can be made in the US by increasing the efficiency of electricity-using machines and through other conservation means than by any other competing approach.

Because of these factors, during its first year, the "fresh look" study focused on the energy needs of nations outside the OECD (Organization for Economic Cooperation and Development). In addition, due to the problems of using very large amounts of power terrestrially, and to reduce initial investment costs, the study examined non- GEO concepts with total power output measured in the 100s of Megawatts rather than Gigawatts.

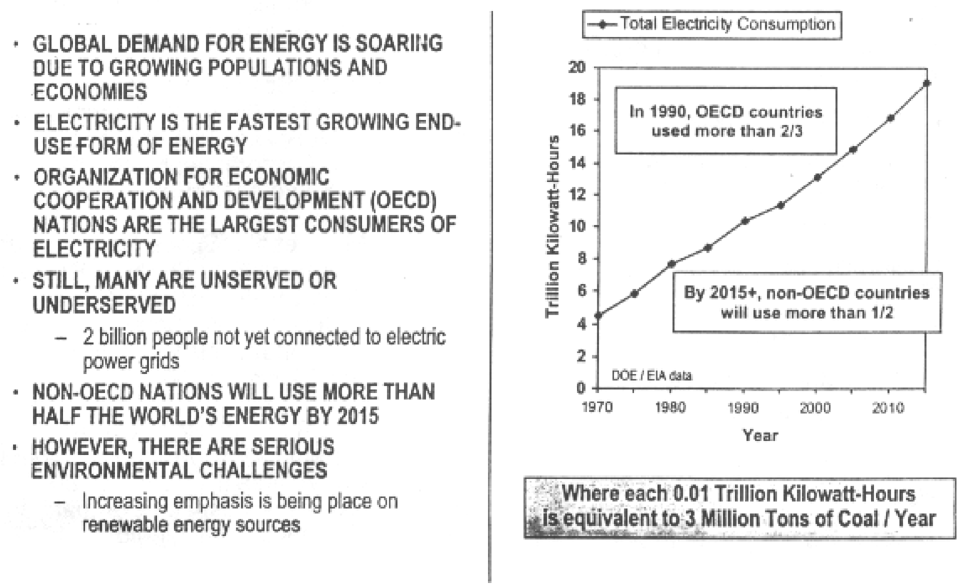


Figure 2: Projected Growth in Global Electrical

SSP Technologies and Systems

A number of innovative and advanced technologies were investigated by the "fresh look" study for each major aspect of an SSP system, including: the space segment, the ground segment, space infrastructure, and transportation.

Space Segment Conventional structures as were very innovative approaches, such as large gossamer structures. In addition to implementation of the space segment as a single, unitary system, constituting the systems or arrays from a number of independent sub-units were considered. Alternative configurations were examined, including conventional solar array/transmitter layouts with three-axis stabilization, and innovative configurations that exploit a gravity gradient approach.

Various means of solar energy conversion were examined, including planar solar arrays, concentrator solar cells, and solar dynamic systems. Various single and multiple tailored band-gap cells were considered, with various levels of concentration.

Diverse innovative approaches to transmitting power from space were examined, including microwave, millimeter wave, and optical/laser wavelengths. Various means of generating the beam power were considered, including magnetrons, klystrons, gyrotrons, and Free Electron Lasers

(EELs). The impacts of beam frequency on both space and Earth were assessed - albeit in a very preliminary fashion - including interference and likely biological effects. Construction of the antennas in a single unit array and multiple independent, but coordinated, unit alternatives were considered. Several forms of integration of the transmitters and antenna were treated, as were lasers and millimeter wave concepts. Finally, various approaches to space segment deployment, operations and servicing were considered.

Several major new system concepts were defined as a result of the fresh look study. These included:

* The "SunTower" - a gravity gradient stabilized, space tether-based SSP system concept involving the use of highly-modularized power generation (with inflatable solar concentrators) and power transmission (using mass-produced magnetron segments), and

* The "SolarDisk" - a rotationally stabilized, GEO-based SSP system concept using differentially-spinning elements.

Ground Segment. The ground segment was receiving systems and the means to transmit the electricity to intermediate distribution levels locally. For distributed receiver architectures, the ground segment could also include load leveling systems (particularly for niche markets). The required size fencing to prevent radiation outside the perimeter to exceed the lowest of any national standard was addressed.

Space Infrastructure. Reliance on in-space or system-unique space infrastructure was minimized in the "Fresh Look" study as a strategy for reducing the cost of initial system development, deployment and operations. The use of humans in space was minimized except where their presence had the potential lower life cycle costs. Conversely, the use of automated/ autonomous systems or robotics was maximized.

Transportation. Earth-to-orbit and in-space transportation are crucial to the success of any SSP concept due to the large masses required for power generation and transmission for all known concepts. Transportation requirements were assessed as a function of potential markets/prices, including near-, mid-, and far-term options. Overall, transportation system concepts that could deliver SSP elements to LEO for costs on the order of $100-$200 per pound and to GEO for costs on the order of $1000 per pound appear feasible.

SSP Architectures

Several related but distinct architectural approaches to the problem of space solar power were identified as a part of the "Fresh Look" study. These include:

* LEO, sun-synchronous constellations of SSP satellites with relatively low frequency power transmission,
* Middle Earth orbit (MEO) constellations of 5SF satellites with relatively low to intermediate frequency power transmission,
* LEO power generation with higher orbit Power Relay Satellites (PRS) in MEO or Geostationary Earth Orbit (GEO) with a range of potential frequencies for power transmission,
* Small-scale GEO SSP satellites with high-frequency power transmission,
* Large-scale GEO SSP satellites with various potential frequencies for power transmission, and
* Extremely large-scale systems involving multiple SSP and PRS satellites with various potential frequencies for power transmission in LEO, MEO and GEO.

The following section describes in more detail the two major concepts that emerged from the "fresh look" study.

"FRESH LOOK" SSP CONCEPTS

The "SunTower"

The "SunTower" SSP concept exploits several innovative approaches to reduce the development and life cycle cost of SSP, while at the same time broadening market flexibility. The system concept involves an extensively evolvable and modular space segment, initially deployed in low Earth orbit and later migrating to an elliptical Earth orbit. A single satellite/ground receiver 'pair' would be sized to approximately 100-400 MW scale, with multiple satellites required to maintain constant power at that level. This concept is depicted in **Figure 3**.

SSP: Development & Manufacturing. This concept, owning to its extensive modularity, will entail relatively small individual system components which can be developed at a moderate price, ground tested with no new facilities, and demonstrated in a flight environment with a sub-scale test. Manufacturing can be 'mass production' style from the first satellite system.

Ground Launch Infrastructure. No concept-unique ground launch infrastructure is required, beyond that necessary to achieve extremely low launch costs (on the order of $200-$400 per kg).

Earth-to-Orbit Transportation. No concept-unique ETO transportation system is required, beyond that necessary to achieve extremely low launch costs (on the order of $400 per kg), with payloads of greater than 10 MT; this is consistent with Highly Reusable Space Transportation

(HRST) system concepts. (The HRST study and its results are discussed in IAF-97-V.3.06.)

In-Space Infrastructure. No unique in-space infrastructure is required for initial system deployment, which takes place in LEO. However, it is assumed that the launched systems include modular assembly-support systems. These consist of a clever mechanical scheme inherent in the structure.

In-Space Transportation. No permanent in-space transportation is required for initial system deployment, which could take place in LEO or (better) at an intermediate staging orbit (e.g., 1200 km. Two functions must be met by the in-space transportation approach: (1) transport of the 5SF to its operational orbit (this may be an inherent function of the SSP - e.g., using SEPS), (2) transport of new or replacement elements to the operational orbit and return for de-orbit of replaced elements.

SSP: Space Segment. The "SunTower" concept is a constellation of medium-scale, gravity gradient-stabilized, RF-transmitting space solar power systems. Each satellite resembles a large, Earth-pointing sunflower in which the face of the flower is the transmitter array, and the 'leaves' on the stalk are solar collectors. The concept is assumed to transmit at 5.8 GHz from an initial operational orbit of 1000 kin, sun-synchronous, at a transmitted power level of about 200 MW RF. Total beam-steering capability is 60 degrees (+30 degrees). A single transmitting 'element, is therefore projected to be a hexagonal surface approximately 5 cm in diameter. These elements are pre-integrated into 'sub-assemblies' for final assembly on orbit. For 200 MW transmitted RF power, the transmitter array is an 'element and subassembly -tiled plane' that is essentially circular, approximately 260 meters in total diameter, and approximately 0.5-to-1.0 meters in thickness.

Sunlight-to-electrical power conversion must be modular

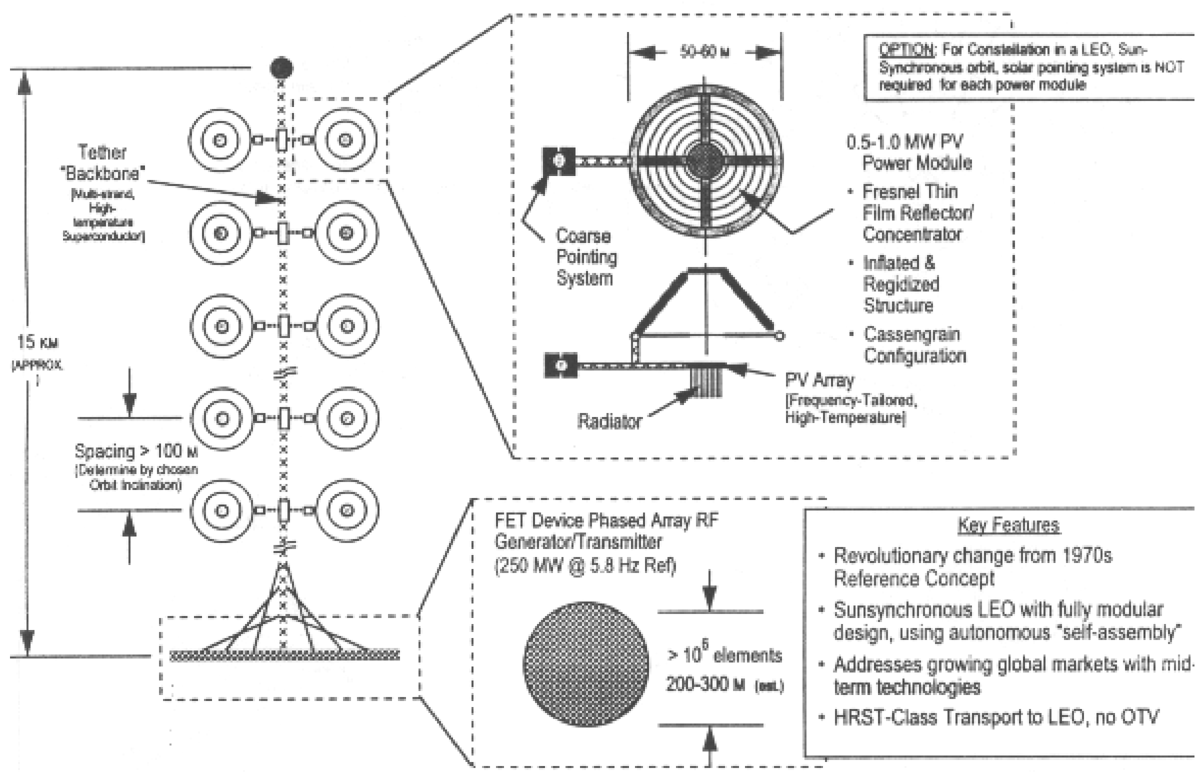


Figure 3: The "Sun Tower" SPS Concept (MEO constellation)

and deployable in "units" about 50-100 meters in diameter with a net 1 MW electrical output (approximately). The primary technology option is a gossamer-structure based reflector with non-dynamic conversion at the focus (e.g., advanced photovoltaics); this reference is subject to trade studies. These collection systems are presumed to be always sun-facing (with the system in a sun-synchronous orbit) and to be attached regularly in pairs along the length of a structural/power transmitting tether to the backplane of the transmitter array. Heat rejection for power conversion and conditioning systems is assumed to be modular and integrated with power conversion systems.

Heat rejection for the transmitter is assumed to be both modular and integrated at the 'back-plane' of the transmitter array. Power transmission lines from the single, central tether attachment point to the backplane are assumed to be integrated with the modular sub-assemblies of the array.

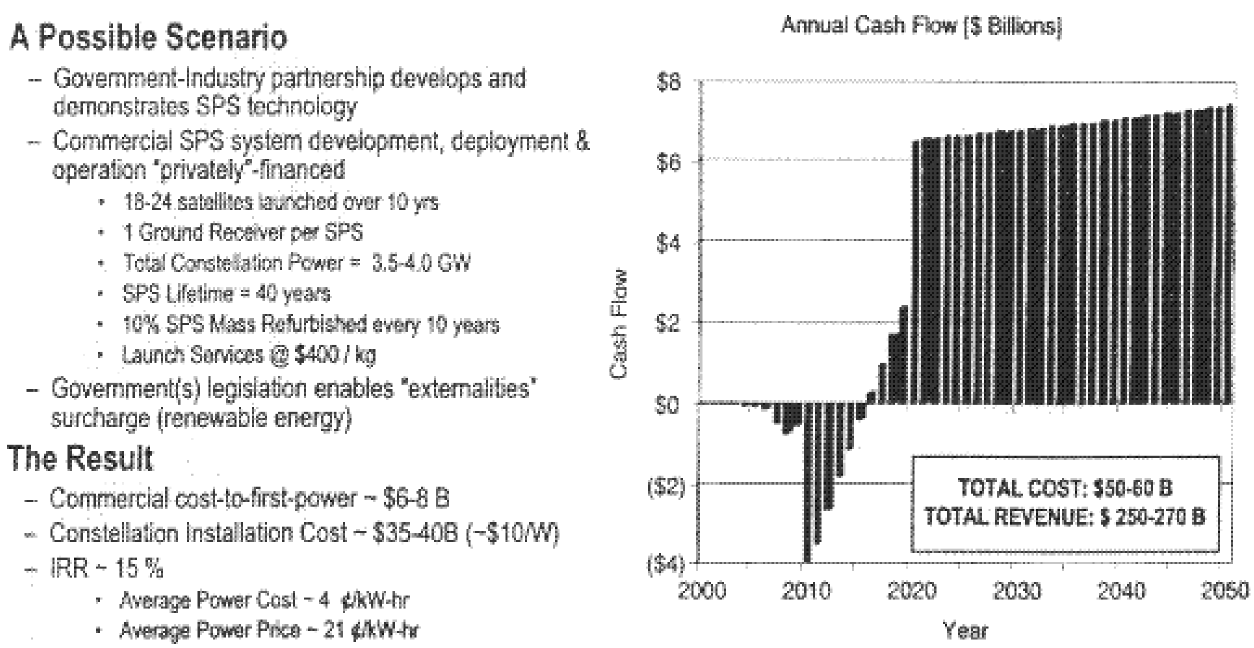


Figure 4: Representative Financial Performance for the "SunTower SPS (MEO) Scenario

SSP: Ground Segment. The nominal ground receiver for the SunTower concept is a 4km diameter site with direct electrical feed into the commercial power utilities interface. The space segment is consistent with a variety of ground segment approaches; however during the early years of operations, multiple ground stations would be required to achieve reasonable utilization of capacity. For primary power, a ground-based energy storage system would be required, in particular in the early phases of overall system deployment in which only a single SunTower was operational.

Commercial Power Utilities Interface. This interlace may be one of several types, including single site power into the grid.

Markets. Electrical energy markets on a global basis could be served by a single SunTower satellite with incremental increases in coverage with expansion of the space segment to a constellation.

Financial Factors. The "SunTower" concept is projected to be achievable for a cost-to-first-power on the order of $8 B to $15 B (for a 250 MW platform. This represents a factor of 30 reduction below the comparable investment required for the 1979 Reference System. **Figure 4** illustrates the financial performance for a SunTower architecture involving 18 SPS, deployed over 10 years.

The "SolarDisc"

Summary. The "SolarDisc" space solar power concept exploits a revolutionary paradigm shift to reduce the development and life cycle cost of a large geostationary orbit. In particular, the system concept involves an extensively axisymmetric, modular space segment which 'grows' in geostationary Earth orbit (GEO), and can provide an early 'online' capability at a reduced power level (see **Figure 5**). A single satellite/ground receiver 'pair' would be used; this pair can be sized according to the specific market, ranging from approximately 1 GW to 10 GW scale.

SSP: Development & Manufacturing. This concept, owning to its extensive modularity, will entail relatively small individual system components which can be developed at a moderate price, ground tested with no new facilities, and demonstrated in a flight environment with a sub-scale test. Manufacturing can be 'mass production' style from the first satellite system.

Ground Launch Infrastructure. No concept-unique ground launch infrastructure is required, beyond that necessary to achieve extremely low launch costs (on the order of $200 per pound).

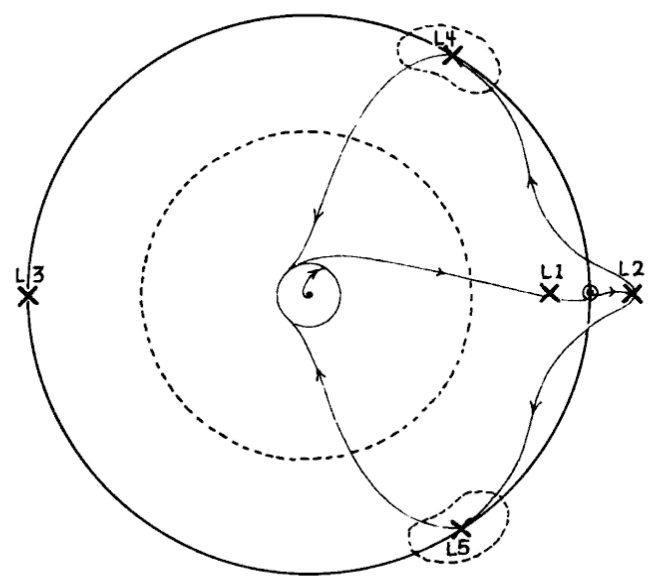
Earth-to-Orbit Transportation. No concept-unique ETO transportation system is required, beyond that necessary to achieve extremely low launch costs (on the order of $200-$400 per kg), with payloads of greater than 10 MT; this is consistent with HRST.

In-Space Infrastructure. A unique in-space infrastructure is required for system deployment. An extremely affordable LEO-to- GEO in-space transportation system is vitally important to this concept. It is also assumed that the launched systems will include modular assembly-support systems. These must consist of both a clever mechanical scheme inherent in the structure as well as sophisticated and mobile, self-contained robotics approach - e.g., 'spiders'.

In-Space Transportation. A unique in-space transportation is required for initial system deployment, which takes place in LEO. An extremely affordable LEO-to-GEO in-space transportation system is vitally important to this concept.

The SolarDisc configuration discussed here is different from that presented in the April 4,1997, Fresh Look Study Report in several ways. There were two major issues with the original configuration. First, the placement of the RF transmitter at the center of the rotating PV array disc necessitated "dual lodes" in the phased array. This approach resolved the problem of providing continuous transmission when a single transmitter would have been blocked by the solar array, but led to an unacceptable increase in the system mass. The second major issue with the initial SolarDisc configuration was that of how to provide the mechanical and electrical interface between the spinning PV array and the stationary, Earth-pointing phased array. The new configuration resolves both of these issues.

SSP: Space Segment. The "SolarDisc" concept is a single, large-scale GEO-based, RF-transmitting space solar power systems. Each satellite resembles a large, Earth-pointing disc which is approximately 3-to-6 kilometers in diameter. This disc is continually Sun-pointing. The center of the disc is occupied by a hub which integrates the power from each segment of the PV disc. This power is conveyed via two redundant structures (like the fork on the front wheel of a bicycle) to a continually Earth-pointing phased array that is approximately 1 kilometer in diameter. The concept is assumed to transmit at 5.8 GHz from an operational GEO location, at a transmitted power level of 2-8 GW RF. Total beam-steering capability is 10 degrees (+/- 5 degrees). A single transmitting 'element' is projected to be a hexagonal surface approximately 5 cm in diameter. These elements are integrated into 'sub-assemblies' for final assembly on orbit. The transmitter array is an 'element and sub-assembly-tiled plane' that is essentially circular, about 1000 meters in total diameter, and approximately 1 .5-to-3.0 meters in thickness.



Sunlight-to-electrical power conversion is via thin-film PV array. This system is anticipated to be largely modular at the sub-element level and deployable in "units" that represent a single concentric ring of 2-4 meters in width. The collection system is intended to be always sun-facing (with orientation by angular momentum). Heat rejection for power conversion and conditioning systems is assumed to be passive, but where active cooling is needed, to be modular and integrated with power transmission systems.

SSP: Ground Segment. The nominal ground receiver for the SolarDisc concept is a 5-6+ km diameter site with direct electrical feed into a local utilities interface. The space segment is consistent with a variety of ground segment approaches. In particular, multiple ground sites (e.g., on order 10-20) could be served from a single SolarDisc SPS with time-phased power transmission. For primary power, no ground-based energy storage system would be required.

Commercial Power Utilities Interface. This interlace may be any one of several diverse types (options to be assessed), including single site power into the grid.

Markets. Electrical energy markets on a global basis could be served by a single SolarDisc satellite with incremental increases in power level from a single satellite (as the SolarDisc grows), and with expanded coverage from a single satellite with addition of multiple ground segments, and with further expansion of the space segment to a constellation of at least three-to-four satellites covering the majority, of the Earth's energy markets.

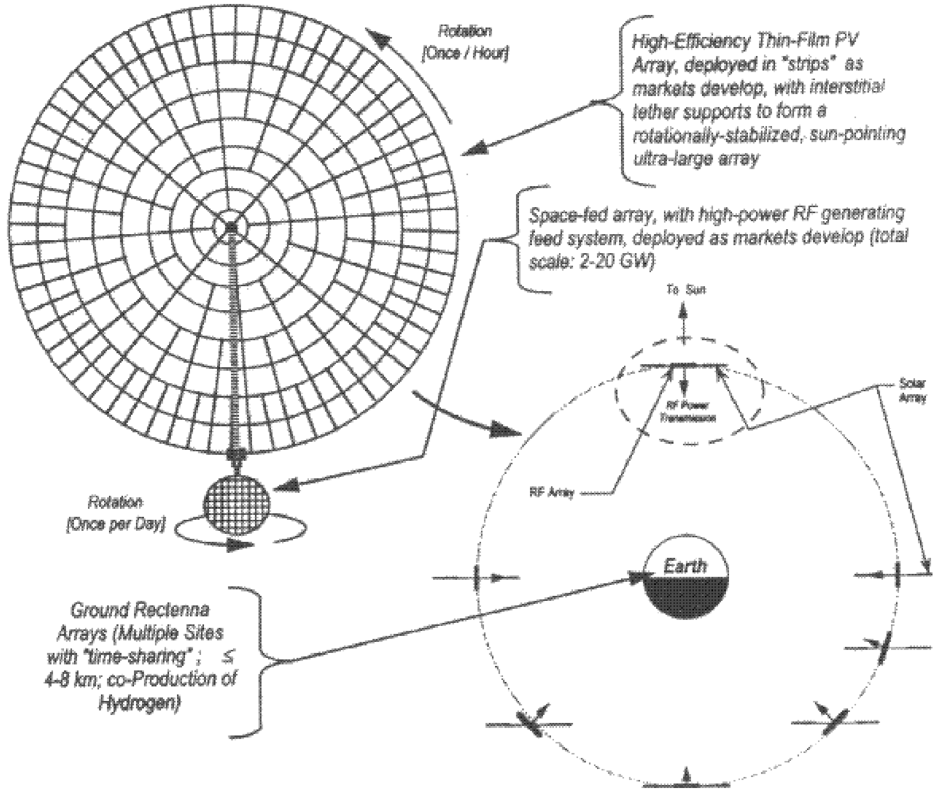


Figure 5: Depiction of a 5 GW "SolarDisc" SPS System Concept

Financial Factors. The "SolarDisc" is projected to be achievable for a cost to first power on the order of $30B-$50 B for a 5 GW platform. Although still large, this represents a factor of 5 reduction below the comparable investment required for the 1979 Reference System. **Figure** 6 illustrates the financial performance for a SolarDisc architecture with 6 SPS, deployed over 30 years.

SPACE APPLICATIONS OF SSP

A preliminary assessment of potential space applications of the technologies and system concepts defined as a part of the "fresh look" study is being conducted. Preliminary findings suggest that a wide variety of these potential applications exist

Science Missions

Several space science applications of advanced SSP technologies can be identified. For example, Solar Electric Propulsion System (SEPS) stages for outer planet robotic science missions, non-RTG/nuclear power for Jupiter robotic science missions (in the 1 kW-class or more) with the option for high-rate communications. (This approach integrates the power collector and the RF communications antenna - the so-called a "power antenna" approach created by the Jet Propulsion Laboratory.)

SSP systems may be applied for very large space observatories based in a solar orbit several times farther from the sun that the Earth is which are capable of finding and studying Earth-like planets around near-by stars deep space (this is the so-classed "Planet-Finder" science mission concept). Another application is in integrated radar and/or high-rate communications for science missions to the asteroids, comets, or other small solar system bodies.

Commercial Missions

Various commercial applications can be identified. SEPS stages for commercial GEO satellites may be developed. Also, high levels of on-board power for these satellites may be of interest. Finally, affordable power for farther-term future space business parks could be readily developed from space solar power systems.

Exploration Missions

Lastly, there are a number of potential applications of these technologies in future human exploration missions, including the moon, Mars and asteroids in the inner solar system. These include: megawatt-class SEPS Lunar cargo

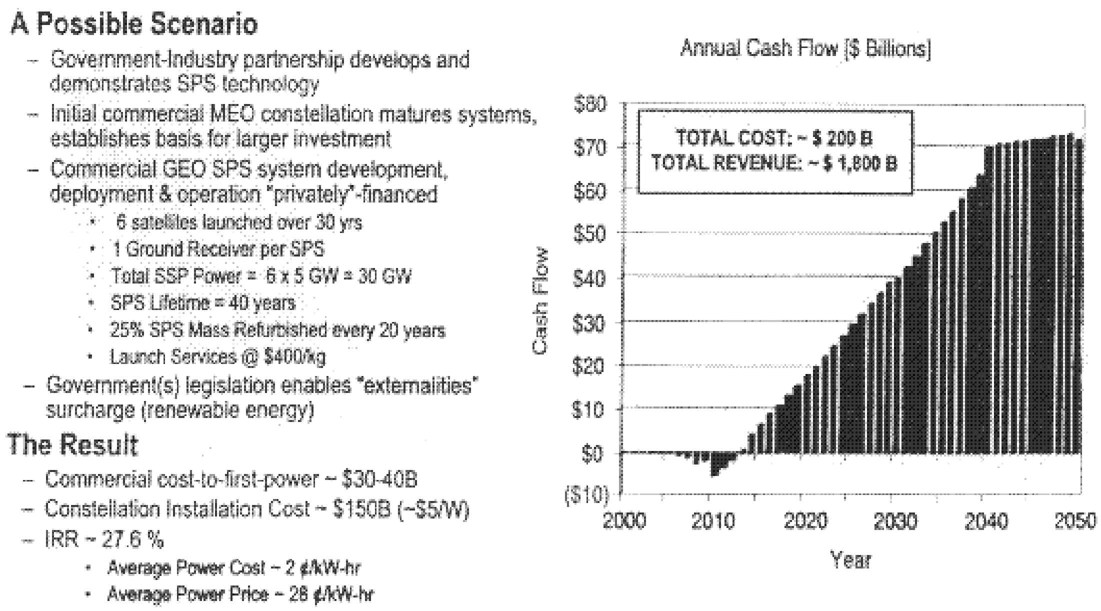


Figure 6: Financial Performance for a Typical "SolarDisc" SPS Scenario

space transfer vehicles Lunar orbit WPT for Lunar surface power affordable human Mars mission transportation systems.

Of these, the concept of using multi-megawatt-class space solar power systems to achieve very low cost Mars mission concepts appears to have particular leverage. By using systems that are amenable to low-cost, multi-unit, modular manufacturing, even though the overall system masses are not lower, the cost appears to be significantly lower. Example: The "SolarClipper". An especially intriguing opportunity is that of using affordable megawatt-class space power for interplanetary space missions. It appears to be possible to reduce the cost for Earth surface-to-Mars orbit transportation dramatically through the use of very advanced, large-scale space solar power in a solar electric propulsion system (SEPS) approach. The basic architectural strategies of the SolarClipper concept are straightforward:

1. Use low-mass/high-efficiency space solar energy, rather than nuclear energy, as the basic power system;

2. Modularize transportation systems into packages of less than 40,000 pounds each to enable launch of all but selected surface systems, with resorting to heavy lift launch vehicles (HLLVs);

3. Fabricate multiple identical SEPS systems to enable effective mass production at dramatically lower cost per unit weight of purchased hardware; and,

4. Use "brilliant" systems architectures that can assemble themselves in Earth orbit with little more than autonomous rendezvous and docking technologies;

5. Exploit the higher fuel efficiency ("specific impulse" of electric propulsion to offset the mass associated with modularity of systems and interconnections between systems assembled in space.

Because the majority of a mission's mass could be transported to Earth orbit on lower cost vehicles, a substantial savings (perhaps a factor of 2-to-3) in launch costs might be achieved. Because most system elements are mass-produced, costs per unit weight could be reduced by as much as a factor of 10.

As an added advantage, SolarClipper cargo transfer vehicles can - once they reach Mars orbit - be deployed for use as operational solar power satellites using wireless power transmission to provide essential energy to surface operations (thus eliminating the need for Mars surface nuclear reactors). This combination of SEPS for Earth-Mars transport, and SPS WPT at Mars, could make possible non-nuclear exploration architectures (at least within the inner solar system).

CONCLUSIONS

The increasing global energy demand is likely to continue for many decades. New power plants of all sizes will be built. However, the environmental impact of those plants and their impact on world energy supplies and geopolitical relationships can be problematic. Renewable energy is a compelling approach - both philosophically and in engineering terms. However, many renewable energy sources are limited in their ability to affordably provide the baseload power required for global industrial development and prosperity, because of inherent land and water requirements.

Based on the recently-completed "fresh look" study, space solar power concepts may be ready to reenter the discussion. Certainly, solar power satellites should no longer be envisioned as requiring unimaginably large initial investments in fixed infrastructure before the emplacement of productive power plants can begin. Moreover, space solar power systems appear to possess many significant environmental advantages when compared to alternative approaches to meeting increasing terrestrial demands for energy - including requiring considerably less land area than terrestrially-based solar power systems.

The economic viability of such systems depends, of course, on many factors and the successful development of various new technologies - not least of which is the availability of exceptionally low cost access to space. However, the same can be said of many other advanced power technologies options. Space solar power may well emerge as a serious candidate among the options for meeting the energy demands of the 21st century.

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

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