

SPACE SOLAR POWER: A PROSPECTIVE FUTURE ENERGY SOURCE?

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Introduction

Consideration is being given to large-scale space solar power (SSP) technologies and concepts for a number of possible applications during the next 10–30 years and beyond. These possible applications of SSP include many government space missions, such as robotic space and Earth science missions and integrated human/robotic space science and exploration activities in the near-, mid- and far-term. They also include commercial opportunities, such as improved power sources for existing space markets in the near-term, capabilities for new space industries in the mid-term, and in the far-term the eventual delivery of power from space into terrestrial markets. The application of SSP technologies to develop solar power satellites (SPS) that provide power to terrestrial markets is of particular interest to many. During the next several decades, there will be a pressing need for new baseload electrical power generation capacity within the global energy marketplace. However, concerns are also growing that the predominant use of fossil fuels (coal, oil and natural gas) in meeting these demands and the concomitant increase in greenhouse gas emissions may result in significant climatic changes. Potential space applications are equally important. Various ambitious government mission concepts such as interstellar probes, human outposts on the Moon or human exploration of Mars, and others, will only happen if new space power sources are developed—of which SSP is one important candidate.

This paper provides a brief review of past studies of SSP and solar power satellites (SPS), beginning with the 1970s and concluding with NASA's 1998 SSP Concept Definition Study (CDS). The paper also summarizes the 1999–2000 US SSP exploratory research and technology (SERT) program, including studies of prospective SSP applications for both government and commercial space systems. Finally, there is a discussion of the potential for SSP to become an option to meet global power needs, with an emphasis on technical approaches that might be achievable within the next 20 years.

Past Space Solar Power Studies

Origins: 1960s–1970s

Dr. Peter Glaser introduced the concept of generating solar power in space for use in terrestrial markets on Earth in 1968. This idea—solar power satellites—has captured the imagination of many visionaries around the world during the intervening decades. However, the prospect of SPS implementation is exceptionally challenging. It depends on a wide

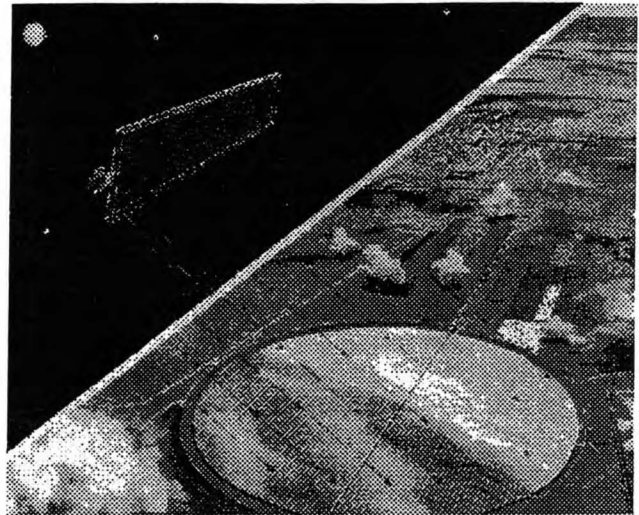


Figure 1 The 1979 Solar Power Satellite Reference System

variety of technical advances, and is enabled by the technology of wireless power transmission (WPT). As a result of relevant technological advances in the early 1970s, the US Department of Energy (DOE) and NASA conducted major SPS systems studies during 1976–1980. These studies placed emphasis on a particular approach—the “1979 SPS Reference System”—that would have required an investment of about \$250B (US\$, '96) prior to the delivery of the first kilowatt-hour. Figure 1 provides an illustration of some of the major system elements of the 1970s system approach.

However, all serious work on SSP in the US¹ was discontinued around 1980. Some of the factors involved included:

- The cost-to-first power > \$250B ('96,\$) for the 1979 SPS Reference System
- Massive initial government investment in infrastructure required
- Too many dramatic advances in technology needed
- Largely a “US-only” proposition with poor international involvement
- Reagan Administration (1980–1981) had other priorities
- US OTA and NRC criticized early deployment (1990s) scenario strongly
- Urgency faded as oil prices plummeted in the early 1980s

¹Important work relating to SPS continued in the 1980s and early 1990s in other countries, notably Japan, as well as interested private groups in the US; these are not recounted in this paper.

The Fresh Look Study: 1995-1997

During 1995–1997, NASA conducted a “fresh look” at SSP to determine whether recent technology advances might enable an SPS approach that could deliver energy into terrestrial markets at competitive prices. It was determined that several factors had changed since 1980 that might increase the viability of SSP and SPS; these included:

- A huge global market for new energy sources has developed
- Concerns about “Greenhouse Gas” emissions and Global Climate Change are growing
- US National Space Policy calls for NASA to drive ETO costs down dramatically (Independent of SPS/SSP)
- Important technical advances have been made and new R&T avenues identified
- Potential space applications of key technologies/systems have been identified—both for NASA and Commercial Space
- Strong opportunities appear to exist for international interest and involvement.

The Fresh Look Study sought concepts that were technically and economically viable—at a fraction of the investments projected for SSP in the late 1970s—and which could provide power to terrestrial markets without major environmental drawbacks. Figure 2 summarizes the approach taken by the Fresh Look Study to identify such concepts.

Some twenty-nine systems concepts and architectural approaches were examined, resulting in the identification of a handful of key design strategies as well as two particular approaches that seemed promising. One of the two preferred concepts emerging from the Fresh Look study is the “SunTower” SPS, which would provide power to global markets. This concept, shown in Figure 3, exploits a variety of innovative technologies and design approaches in achieving—analytically, at least—technical and programmatic feasibility for initial commercial SSP operations. Capable of being deployed to various orbits, the SunTower involves min-

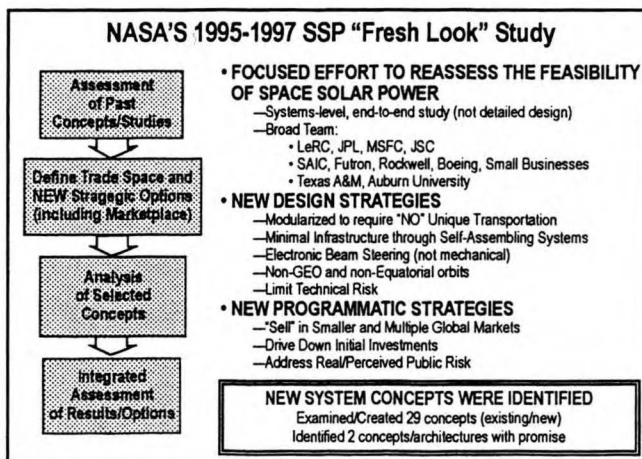


Figure 2 The 1995–1997 SSP “Fresh Look” Study

- **System Concept**
 - Modular systems; self-assembling at high GEO
 - Gravity-gradient/IGN&C stabilized
 - Aggressive technology for solar arrays, integrated propulsion, others
 - RF phased array for Wireless Power Transmission
 - >> ± 5 degrees Beam Steering
- **Architecture**
 - Geostationary Earth orbit
 - ± 40 degrees Latitude Coverage
 - Power services of ~ 1200 MW (example)
 - Requires low-level terrestrial energy storage
 - 30 SPS yields power to >30 sites, etc.
 - Power for Emerging Markets: South & Central America, Africa, Asia, India ...
- **Transportation**
 - Deployment using Commercial Launch Services (RLG-class @ \$400/kg)
 - In-space using advanced SEPS (expedient or reusable options)

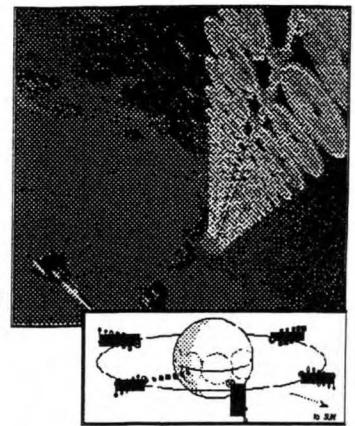


Figure 3 The “SunTower” Solar Power Satellite Concept (GEO Option)

imal fixed in-space infrastructure and does not require a heavy lift launch vehicle (HLLV). The concept appears to allow at least a ten-fold reduction in initial investment compared to the 1979 SPS Reference System. A number of potential non-SPS space program uses of SSP and related technologies were identified, including human exploration, space science and commercial space applications.

By Spring 1997, NASA’s “Fresh Look” study had concluded that space solar power concepts and technologies—and perhaps SPS—appeared to be much more technically and economically viable than in the past. As a result, the US Congress expressed interest in SSP in November 1997, and suggested that NASA should undertake a follow-on to the “Fresh Look” study. In response, during 1998 NASA conducted a \$2M SSP Concept Definition Study (CDS).

The 1998 SSP Concept Definition Study

Goals and Objectives. The 1998 SSP Concept Definition Study (CDS) had three primary goals:

- Identify, define and analyze innovative systems concepts—using new concepts and technologies—that could generate solar power in space for transmission to, and use in, terrestrial commercial markets
- Determine the technical and economical feasibility of such space solar power systems concepts
- Develop a preliminary plan of action for the US (working with international partners) to undertake an aggressive technology initiative, in which NASA would play a major role, to enable future private sector development of a commercially-viable space solar power industry

In pursuit of those goals, the objectives of the 1998 SSP CDS were to:

- Identify and/or refine one or more commercially-viable approaches to Space Solar Power (SSP) for terrestrial application (with needed technology advances)

- System concepts, technologies, infrastructure (including space transportation systems), and economic scenarios
- Develop strategies for the utilization of SSP concepts for space science and exploration
 - ⇒ Emphasizing revolutionary applications of SSP technologies to space transportation for both human and robotic missions
- Determine the likely scope and character of any potential partnerships that could be created to pursue later SSP technology development and demonstration efforts
- Define technology development and demonstration roadmaps for critical SSP elements including performance objectives, resources and schedules
 - ⇒ Including “dual-purpose” applications (commercial, science, and other government)

Approach and Organization. In order to accomplish its broadly stated goals and objectives in the allowed time (i.e., about six months), the 1998 SSP CDS effort was organized into a diverse set of focused teams—each addressing a specific aspect of the overall challenge. Each of the several teams was organized distinctly, but the results were cross-pollinated through a series of working integration meetings (which involved the use of Integrated Product Teams [IPTs] spanning the various topics). Figure 4 provides a detailed flow diagram of the 1998 SSP CDS study approach.

The paragraphs that follow discuss in more detail several aspects of the study.

Space Transportation. Exceptionally low cost space transportation—both for getting into orbit and once in space—is of paramount importance to the possible viability of solar power from space. The 1998 SSP CDP examined this challenge from several perspectives and with several different systems concepts. A primary issue was the size of the standard SSP “package”. (A large package (e.g., 80 MT or greater) reduces in-space assembly requirements, but drives up initial ETO transportation infrastructure costs, while a smaller standard SSP package has the opposite effect.)

Concepts included four different approaches derived from the 1996-1997 highly reusable space transportation (HRST) study in the 10–20 metric ton range, with a side examination of a 40 metric ton case being considered. HRST derived options included:

- (1) advanced vertical take-off, horizontal landing (VTHL) rocket based system (analogous to an advanced reusable launch vehicle (RLV) type system,
- (2) horizontal take-off, horizontal landing (HTHL) rocket based system with the use of ground-based launch assist (i.e., a catapult),
- (3) HTHL system with a rocket-based combined cycle (RBCC) propulsion system and launch assist, and
- (4) HTHL all RBCC system without launch assist.

In addition, parallel studies of an HLLV approach (with an 80 MT payload) were conducted. The overall conclusions of these studies were: (1) that at the very high flight rates required for SPS launch and operations (more than 1000–2000 flights per year), launch prices of \$400/kilogram were achievable; (2) that they could be reached with not one, but several concepts; and (3) that the best of the studied concepts was the HTHL system with an RBCC propulsion (known as “Argus”) and launch assist (using the “MagLifter” concept).

Low cost transportation once in space is of equal or greater importance to the cost of ETO. Several architectural and technological options were evaluated. Findings included (1) that highly fuel-efficient solar electric propulsion systems are required for the primary transport from LEO to a higher operational orbit (i.e., MEO or GEO), and (2) that reusable in-space transportation infrastructures are needed to achieve the lowest cost contribution.

Independent Economic and Market Analysis Team (IEMAT). Within the SSP CDS, the IEMAT team had a special and independent role of determining the market potential for new renewable power systems—such as SSP—within the global marketplace of 20-30 years hence. Led by Resources for the Future (RFF) and involving a range of consultants and non-aerospace industry, the IEMAT effort determined the financial and policy “boundary conditions” for possible future SSP systems. The general findings of the IEMAT included the following:

- The global demand for energy (especially electricity) will continue to grow dramatically through the next 20-30 years,
- It is not clear at this time what global climate change policy decisions will be—nor the impact of such decisions on costs/benefits of renewable versus carbon-fueled baseload power options,
- Significant SSP technology uncertainty currently exists
- Therefore, space solar power system development will not be commercially viable in the near- or mid-term,
- Government must take the lead role in SSP (or any other long-term) energy technology R&D

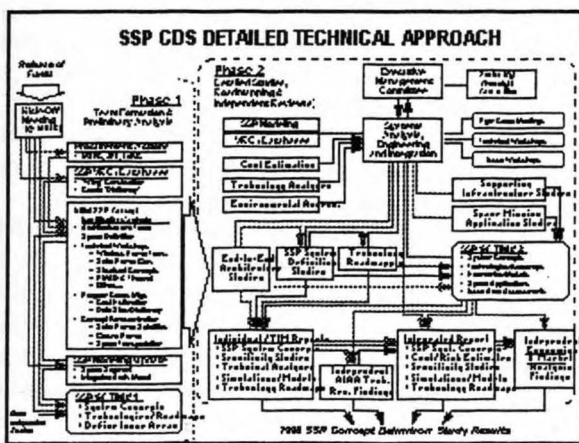


Figure 4 1998 SSP Concept Definition Study Detailed Technical Approach

- Partnerships between government and industry are possible, if not likely, for interim R&D objectives,
- To be viable in the far-term (2020 and later), SSP should be capable of providing power at a cost of no more than about 5.5¢–7.5¢ per kWh for global markets.

Some of the factors that will affect the eventual viability of SSP for terrestrial markets include: (a) future international market demand for energy, (b) competing and complementary technology options, (c) the continuing availability of low-cost fossil fuels, (d) local or regional “higher prices” in developing nations compared to those in the Organization for Economic Cooperation and Development (OECD) nations, and (e) global climate change science, international perceptions and policy initiatives (such as the Kyoto conference).

This subject is discussed in more detail in the latter portion of this paper.

Space Applications. One of the areas of emphasis for the study was an examination of prospective space applications of SSP technologies and systems concepts. Various opportunities were examined, including both government and commercial missions. Of the former, both space science and human exploration applications appeared to be quite significant. For example, prospective space science applications included both nearer-term options, such as advanced solar electric propulsion systems (SEPS), as well as farther-term options, such as the eventual use of large-scale SSP systems to enable beamed power propulsion systems for interstellar precursor probes.

For the human exploration and the development of space, an even broader range of potential applications were identified. Exploration applications ranged from early improvements in power for Earth orbit systems (such as the International Space Station), to Lunar surface power, to power for interplanetary transportation systems, and eventually power for Mars orbit-based SPS providing power to planetary surface operations. Commercial development of space applications were identified in the near-term (e.g., advanced power for large geostationary Earth orbit (GEO) communications satellites), in the mid-term (e.g., low-cost power for low Earth orbit (LEO) new space industries, such as commercial research parks) and in the far-term (e.g., the solar system resources development and utilization).

Deliverables. NASA’s 1998 SSP CDS resulted in the affirmation of the Fresh Look study result that new SSP concepts have emerged which are credible, with technical and programmatic risks identified² and which have the potential to achieve commercial viability. The effort also created an interrelated family of technology road maps providing a strategic perspective on the timeframe and scope of investments that would be necessary to validate and demonstrate enabling technologies. These road maps considered not only

²A review of the systems concepts from the fresh look study was of particular importance because several significant concerns emerged during 1997–1998 concerning the viability of implementing the MEO SunTower systems concept. As a result, alternative approaches and architectures were identified.

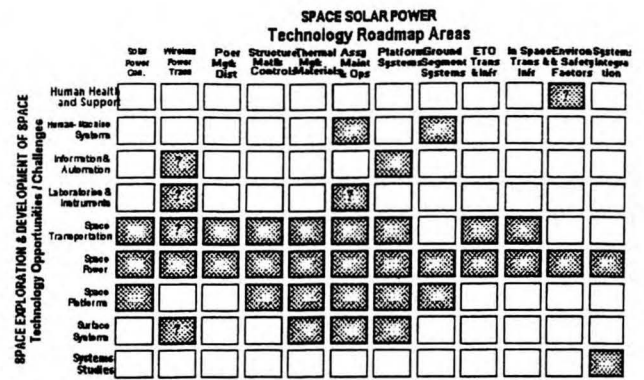


Figure 5 Space Solar Power Technology Areas and Correlation to Space Technology Needs

the eventual application of SSP technology to SPS for terrestrial markets, but also interim space applications (as described above), and assessed the degree to which SSP technologies correspond with those needed for future space science, exploration and commercial missions. Figure 5 summarizes the several areas of SSP technology and provides a “cross-walk” to the technology needs of diverse ambitious future space missions.

In each area (e.g., “wireless power transmission”, “solar power generation”, etc.), a strategic research and technology development approach was defined—supported in detailed technology assessments and expressed in several notional R&D plans consistent with technology readiness in the 2015 timeframe. As a result of strong interest in the SSP concept, the FY 1999 “President’s Budget” proposed the creation of an SSP program with funding of \$5M in FY 1999. Following action by the US Congress, a budget of \$15M in FY 1999 was appropriated for SSP studies and technology. Informed by the SSP Concept Definition Study—and particularly by the technology road maps described above—this budget became the SSP Exploratory Research and Technology (SERT) Program.

The 1999–2000 SSP Exploratory Research and Technology (SERT) Program

The goal of the Space Solar Power Exploratory Research and Technology (SERT) activity is to conduct preliminary strategic technology research and development to enable large, multi-megawatt space solar power (SSP) systems and wireless power transmission (WPT) for government missions and commercial markets (in-space and terrestrial).

Objectives. The objectives of the effort are three-fold. First, defining and modeling systems approaches for the utilization of SSP concepts and technologies, ranging from the near-term (e.g., for space science, exploration and commercial space applications) to the far-term (e.g., SSP for terrestrial markets), including systems concepts, architectures, technology, infrastructure (e.g. transportation), and economics. Second, conducting technology research, development and demonstration activities to produce “proof-of-concept” validation of critical SSP elements for both nearer and

farther-term applications. And lastly, initiating partnerships nationally and internationally that could be expanded, as appropriate, to pursue later SSP technology and applications (e.g., space science, colonization, etc.). By accomplishing these objectives the SERT team plans to make possible informed future decisions regarding further SSP and related R&D investments by both NASA management and prospective external partners. The results of the SERT program should also guide further definition of SSP and related technology roadmaps including performance objectives, resources and schedules; including “multi-purpose” applications (commercial, science, and government).

Approach. Implementation of the SERT is being undertaken by a broadly-based, well-balanced team, spanning several NASA centers, other Agencies, National Labs, US industry and universities, over period of approximately 12 months. The team is examining SSP concepts, options, risks, and provide inputs for future planning by means of a focused portfolio of R&D investments, guided by systems studies with the maximum degree of leveraging of existing resources inside and outside NASA. The activity comprises three complementary elements (with “In-house” and competitively-procured activities):

- *Systems Studies and Analysis:* Analysis of SSP systems and architecture concepts (including space applications). Efforts will include market/economic analyses to address the potential economic viability of SSP concepts, as well as environmental issue assessments, for various potential terrestrial and space markets;
- *SSP Research & Technology:* tightly focused exploratory research targeting “tall poles” and rapid analysis to identify promising systems concepts and establish technical viability to “first-order”; and,
- *SSP Technology Demonstrations:* initial, small-scale demonstrations of key SSP concepts/components using nearer-term technologies, with an emphasis on enabling multi-purpose (space or terrestrial) applications of SSP and related systems/technologies.

Work Breakdown Structure. The challenge of SSP is quite broad, and the work breakdown structure (WBS) for the SERT effort reflects this breadth, including some 14 areas:

- Solar Power Generation
- Wireless Power Transmission
- Power Management & Distribution
- Structures, Materials & Controls
- Thermal Materials & Management
- Robotic Assembly, Maintenance and Servicing
- Platform Systems
- Ground Power Systems
- Earth-to-Orbit Transportation & Infrastructure
- In-Space Transportation & Infrastructure
- Environmental & Safety Factors
- Systems Integration (Analysis, Engineering, Modeling)
- Applications Studies (Science/Exploration/Commercial)

- Independent Economic & Market Analysis

A detailed discussion of the activities in each of these areas is beyond the scope of this paper. The SERT Program will conclude in Spring 2000, with results that will range from refined systems studies to “proof-of-concept” hardware for key technologies. A central issue to be considered again and in still greater detail—and this time in the context of a larger team and ongoing technology investments—will be that of SSP for terrestrial markets: a visionary goal to which strategic R&T plans may be anchored.

Space Solar Power for Terrestrial Markets?

The global energy marketplace is dynamic. Worldwide populations are increasing by about 80 million each year. Industrial outputs and the global “middle class” are growing still more rapidly—leading to significant growth in the per capita consumption of energy in many nations. The US DOE Energy Information Agency (EIA) has projected that the world-wide use of electrical energy will approximately double in the next twenty years—and that it will about double again in the twenty years that follow. In 1990, the nations of the OECD used more than two-thirds of the world’s electrical power production capacity. However, beginning in 2015, the EIA has forecast that use by non-OECD countries will exceed fifty percent of the total capacity and will continue to use an increasing share of the total electrical power generated for an indefinite period.

There are a wide variety of traditional technological options available to meet global electrical power needs, including coal-, oil- and natural gas-burning power plants, nuclear plants, hydroelectric power plants, and others. Nevertheless, fossil fuel burning power plants remain the dominant choice to meet worldwide electrical power demand. Moreover, although significant fluctuations are possible in fossil fuels supply and demand over short time scales, the general trend appears unaffected and world demand will continue to increase during the next several decades.

Growing Atmospheric CO₂ Concentrations. However, the predominant utilization of hydrocarbon fuels for power generation may well have unintended environmental consequences. The International Program on Climate Change (IPCC) and the US Global Change Research Program (USGCRP) recount strong evidence that the Earth’s temperature has increased by 0.5–1.0 degree Fahrenheit during the past century. The cause of this increase is a subject of considerable debate. However, many scientists believe that this increase is the result of human activities—including the unprecedented use during the 20th century of fossil fuels for transportation and electrical power production. As a result, it is expected by the IPCC that further growth in power generation using these fuels will lead to accelerating increases in the level of so-called “greenhouse gases” (predominantly carbon dioxide), and that these increases may lead to changes in global temperatures and climate.

Limiting CO₂ concentrations in the atmosphere might be accomplished through a variety of means, including changes in transportation systems, carbon sequestration strategies such as reforestation, and deployment of new, carbon-neutral power sources. In the US, domestic energy markets are mature: substantial power plants and power distribution systems are in operation providing a total electrical power generation capacity surpassing 700 GW. As a result, important reductions in greenhouse gas emissions may be achievable in the US by increasing industrial, residential and transportation energy efficiency, as well as by other means. This is less so in developing nations where the demand is strongest for new power plants and associated infrastructure to support continuing economic development.

As a consequence, limiting CO₂ emissions globally—while still providing for new power plant capacity (particularly in non-OECD countries)—may require significant new electrical power generation technologies. Naturally, specific CO₂ goals that are established internationally will be critical to determining whether the need is for modest extensions of the state-of-the-art, or for more ambitious new technologies. However, even modest goals may have far-reaching consequences. For example, limiting atmospheric CO₂ concentrations to no more than four-times pre-industrial levels—while meeting global demands for new power plants—may well require bringing into service a wide range of nontraditional energy sources totaling more than 10,000 GW of total capacity by the year 2100.

There are a variety of technological alternatives to fossil fuel power plants. Each has associated with it a range of issues and costs. Of these, solar power options are often viewed as particularly appealing. This appeal derives from various factors, including the possibility of pervasive access to solar illumination globally, its “fuelless” character, its perceived minimal impact on the environment, and low operations and maintenance costs, among others.

Terrestrial Solar Power. In many important applications, terrestrially-based solar power systems have considerable promise. Although these applications have been typically small scale[8], as a result, market demand for new photovoltaic (PV) systems has soared during recent years. Terrestrial solar power systems involve inherent critical limits when considered for large-scale baseload power applications (for example, in the range from 100 MW to 1 GW and higher).

Those limitations involve both the land required for the array and energy storage requirements. At the Earth’s orbit, the sun provides a continuous insolation of approximately 1350 W/m². After atmospheric attenuation, about 1000 W/m² reaches the Earth’s surface at local noon on a clear day. Diurnal variations reduce the local total insolation considerably. In addition, based on the season, the latitude of the site and obstructions on the horizon, the average available sunlight is reduced still further. Rather than 24 kWh/m² per day, the true expected insolation may approach 6 kWh/m² per day for a typical location. For an operational baseload power case, average power levels are not sufficient and local weather patterns must be taken into account as well. Periodic (but unpre-

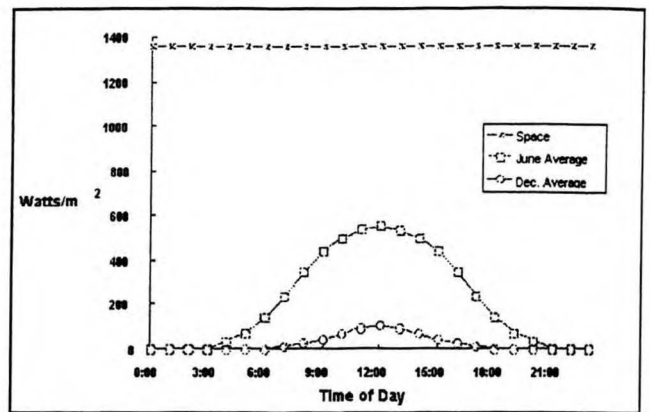


Figure 6 June-to-December Seasonable Variation in Average Solar Insolation (Courtesy B. Erb, Canadian Space Agency)

dictable) and long periods during which power is not available are expected to be unacceptable. Figure 6 illustrates the dramatic seasonal variation (June to December) in the average solar insolation for a typical site in the United Kingdom.

For example, in the case of a 400 MW baseload power requirement, in which a 20% efficient solar array is used to generate power in a single day to support a requirement for continuous power during 5 days following days of overcast sky in winter, the solar array area requirement could be approximately 40,000,000 m². In addition, providing high quality baseload power during the five day requirement would entail an energy storage system with a capacity of approximately 60,000 MWh (assuming 80% input/output efficiency to the energy storage system).

The Space Solar Power Option. As discussed extensively above, one strategy for gaining the benefit of solar power, while avoiding the difficulties of basing such systems on the Earth’s surface is that of the solar power satellite. Many concepts are possible for SPS; one of these—the “SunTower”—has been found in recent studies to show promise that technical and perhaps economical viability might be achievable with substantial research and technology development. Although rigorous cost estimates cannot be formulated without considerably more study and the results of initial technology development efforts, very preliminary estimates suggest that a first *SunTower* SPS might be achievable for a cost-to-first-power of \$20 B (for a GEO-based platform). This represents more than a factor of 10 reduction below the “cost-to-first-power” investment required for the 1979 SPS Reference System. Figure 7 summarizes very preliminary analysis of SSP options versus other terrestrial energy sources in terms of cost-of-capacity, cost-per-kilowatt-hour and carbon dioxide emissions per kilowatt-hour. If validated by future studies, preliminary results suggest that SPS could become viable during the coming century.

Additional studies are needed. It is possible that critical flaws exist in the SSP concepts that have been defined to date. Moreover, numerous technology advances are essential to the SSP performance characteristics described above. These involve very low cost access to space, reusable space

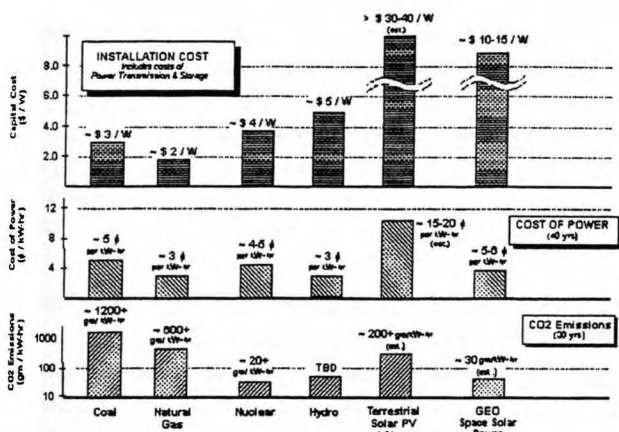


Figure 7 Preliminary Comparison of SSP and Other Terrestrial Energy Sources

systems, very lightweight and radiation tolerant PV arrays, low mass and low cost RF phased arrays for power transmission, autonomous robotic systems, and others. In addition, even once these many technology challenges inherent in the SSP concept are successfully overcome, the difficulty of introducing this new, high-risk technology into the global energy marketplace would still remain.

Summary

Studies during the past four years suggest that—with new technologies and innovative new concepts—large scale space solar power for a variety of space applications is far more viable now than in the past. In addition, the application of very large-scale SSP for terrestrial markets may become viable during the next Century.

Although current world energy supplies are dominated by hydrocarbon fuels, there are increasing pressures to consider non-traditional, renewable energy sources. A gradual development of selected energy options that are not hydrocarbon-based, such as space solar power, might assure that when needed—perhaps as soon as ten to twenty years from now—these options are available for large-scale development and deployment. Solar power systems are philosophically attractive as an alternative for baseload power supplies due to the essentially infinite availability of energy. However, the financial realities of baseload solar power plants on the Earth's surface are dominated by enormous requirements for energy storage systems. This requirement has limited their utilization in essentially all markets. Space solar power plants based in Earth orbits analogous to those used by commercial telecommunications satellites, and transmitting substantial amounts of power into terrestrial markets may represent a new energy option.

Additional studies are needed and considerable technology maturation and validation must be successfully undertaken prior to establishing technical and economic feasibility. These efforts have been initiated at a modest level with NASA's SSP Exploratory Research and Technology (SERT) Program, which will conclude in Spring 2000.

GLOSSARY OF ACRONYMS

CDS	(SSP) Concept Definition Study
DOE	Department of Energy
EM	Electromagnetic
ETO	Earth to Orbit
GEO	Geostationary Earth Orbit
GHz	Gigahertz
GW	Gigawatts
HTHL	Horizontal Takeoff-Horizontal Landing
HRST	Highly Reusable Space Transportation
JPL	Jet Propulsion Laboratory
JSC	(NASA) Johnson Space Center
kW	Kilowatts
kWh	Kilowatt-hour
LEO	Low Earth Orbit
LeRC	(NASA) Lewis Research Center
MEO	Middle Earth Orbit
MSFC	(NASA) Marshall Space Flight Center
MT	Metric tons
MW	Megawatts
NASA	National Aeronautics and Space Administration
OECD	Organization for Economic Cooperation and Development
PV	Photovoltaic
RBCC	Rocket-Based Combined Cycle (Propulsion)
RLV	Reusable Launch Vehicle
RF	Radio Frequency
SEPS	Solar Electric Propulsion System
SPS	Solar Power Satellite
SSP	Space Solar Power
VTHL	Vertical Takeoff-Horizontal Landing
W	Watts
WPT	Wireless Power Transmission

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