CONTENTS OF APPENDICES

Appendix A Microwave Power Transmission Activities in the world

Appendix B Various SPS Models

Appendix C US Activities

NASA SPACE SOLAR POWER ACTIVITIES: 1995-2005

Appendix D Japanese Activities (JAXA reports)

Appendix E European activities (ESA reports)

Solar Power from Space – A Space Contribution to Options for 21st Century Sustainable Energy Systems

Appendix A Microwave Power Transmission Activities in the world

This chapter introduces microwave power transmission (MPT) technology as a base of SPS and its applications. MPT technology was developed in the 1960's by Bill Brown[1,2] based on the prediction that power could be transmitted by electromagnetic waves, triggered by high power microwave generators. Peter Glaser proposed SPS [3] in 1968 by applying this technique to a geostationary satellite.

A.1 Early history

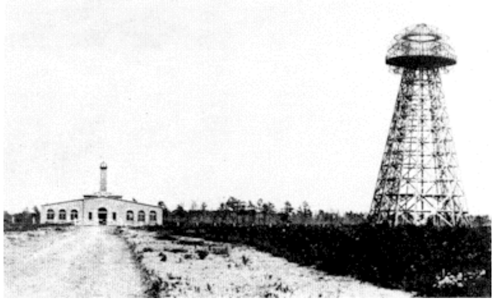

Fig. A.1.1 Tesla Tower.[4]

Brown[1] and Matsumoto[5] review the early history of microwave power transmission. It is recommended to read these reviews. Nikola Tesla first conceived and conducted an experiment based on the idea of wireless power transmission. He used a Tesla coil that was connected to a 60 m high mast with a 90 cm-diameter ball (toroid). The power of 300 kW was fed to the Tesla coil resonated at 150 kHz. The Tesla coil is introduced on the web[6] in detail. Figure A.1.1 depicts Nikola Tesla's historic laboratory and wireless communications facility known as Wardenclyffe, Long Island, New York, USA. The distinctive 57 meter tall tower was demolished in 1917, but the sturdy 28 meter square building still remains standing in silent testimony to Tesla's unfulfilled dream.[4]

The rest of this section is cited from Matsumoto.[5] People were waiting for the invention of a high-power microwave device to generate electromagnetic energy of reasonably short wavelength, since efficient focusing toward the power receiving destination is strongly dependent on the use of technology of narrow-beam formation by small-size antennas and reflectors. In the 1930's, much progress in generating high-power microwaves was achieved by invention of the magnetron and the klystron. Though the magnetron was invented by A. W. Hull in 1921, the practical and efficient magnetron tube gathered world interest only after Kinjiro Okabe proposed the divided anode-type magnetron in 1928. It is interesting to note that H. Yagi and S. Uda, who are famous for their invention of Yagi-Uda Antenna, stressed the possibility of power transmission by radio waves in 1926, thereby displaying profound insight into the coming microwave tube era in Japan. Microwave generation by the klystron was achieved by the Varian brothers in 1937 based on the first idea by the Heil brothers in Germany in 1935. During World War II, development of radar technology accelerated the production of high-power microwave generators and antennas. Continuous Wave (CW) high-power transmission over a microwave beam was investigated in secrecy in Japan. The project, the "Z-project," was aimed at shooting down air-bombers by a high-power microwave beam from the ground, and involved two Nobel prize laureates, H. Yukawa and S. Tomonaga. The Japanese Magnetron was introduced in "Electronics" of USA immediately after World War II. However, the technology of the high-power microwave tube was still not developed sufficiently for practical continuous transmission of electric power. Further more, no power device was available to convert a microwave energy beam back to direct current (DC) power until the 1960's.

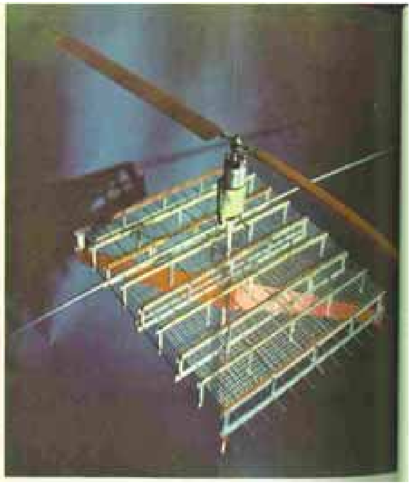

Fig. A.1.2. Microwave powered helicopter. 200 W of power was supplied to the electric motor from the rectenna that collected and rectified power from a microwave beam.[1]

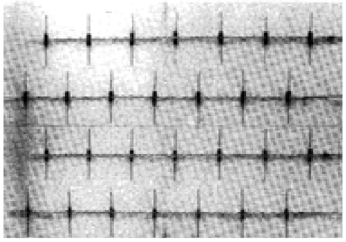

Fig. A.1.3 The first rectenna. Conceived at Raytheon Co. in 1963, it was built and tested by R. H. George at Purdue University. It was composed of 28 half-wave dipoles, each terminated in a bridge rectifier made from four 1N82G point-contact, semiconductor diodes. A power output of 7 W was produced at an estimated 40 percent efficiency.[1]

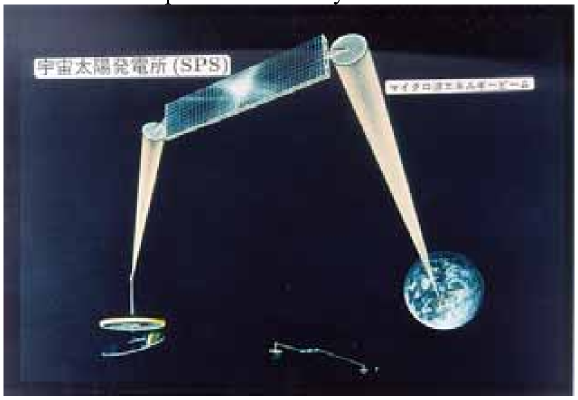

Fig. A.1.4 Artist's view of SPS
©RISH, Kyoto University.

The post-war history of research on free-space power transmission is well documented by William C. Brown, who was a pioneer of practical microwave power transmission. It was he who first succeeded in demonstrating a microwave-powered helicopter in 1964, using 2.45 GHz in the frequency range of 2.4 - 2.5 GHz reserved for the Industrial, Scientific and Medical (ISM) applications of radio waves (Fig. A.1.2). A power conversion device from microwave to DC, called a rectenna, was invented and used for the microwave-powered helicopter. The first rectenna (Fig. 3 in [1]) was composed of 28 half-wave dipoles terminated in a bridge rectifier using point-contact semiconductor diodes. Later, the point contact semiconductor diodes were replaced by silicon Schottky-barrier diodes which raised the microwave-to-DC conversion efficiency from 40% to 84%, the efficiency being defined as the ratio of DC output to microwave power absorbed by the rectenna. The highest record of 84% efficiency was attained in a demonstration of microwave power transmission in 1975 at the JPL Goldstone Facility.[7] Power was successfully transferred from the transmitting large parabolic antenna dish to the distant rectenna site over a distance of 1.6 km. The DC output was 30 kW.

An important milestone in the history of microwave power transmission was the three-year study program called the DOE-NASA Satellite Power System Concept Development and Evaluation Program, started in 1977. This program was conducted to study the Solar Power Satellite (SPS), which is designed to beam down electrical power of 5 to 10 GW from one SPS toward the rectenna site on the ground. The extensive study of the SPS ended in 1980, producing a 670-page summary document. The concept of the SPS was first proposed by P. E. Glaser[3] in 1968 to meet both space-based and Earth-based power needs. An artist's SPS concept is shown in Fig. A.1.4. The SPS will generate electric power of the order of several hundreds to thousands of megawatts using photo-voltaic cells of sizable area, and will transmit the generated power via a microwave beam to the receiving rectenna site. Among the many key technological issues that must be overcome before SPS realization, microwave power transmission (MPT) is one of the most important. The problem involves not only the technological development of microwave power transmission with high efficiency and high safety, but also scientific analysis of microwave impact onto the space plasma environment.

A.2 US Activities

After high-power microwave tubes became available, Brown demonstrated a microwave-powered helicopter in 1964. A focusing ellipsoidal reflector is illuminated with microwave power and a microwave beam is formed (Fig. A.1.2). The helicopter was confined by vertical tether wires. The rectenna (rectifier + antenna) converts microwave directly to direct current (DC) for WPT. The frequency was 2.45 GHz in one of the industrial, scientific and medical (ISM) bands. Later he demonstrated an indoor MPT experiment with 90% dc-dc conversion efficiency.[2] Jet Propulsion Laboratory (JPL) succeeded in transmitting 30kW in the 2.5GHz band from a 26m parabolic antenna to a rectenna 1.6km away (Fig. A.2.1).[7]

Microwave-driven acceleration by photon reflection has been suggested for propelling probes to very high speeds for science missions to the outer solar system and the nearby stars. Beam-driven probes have the advantage that energy is expended to accelerate only the sail and payload, not the propelling beam generator.[8]

Fig. A.2.1. Microwave power transmission over 1.54km

A.3 Canadian Activities

The world's first flight of a fuel-less airplane powered by microwave energy transmitted from the ground took place in Canada. This system is called SHARP (Stationary High-Altitude Relay Platform, Fig. A.3.1), and its 4.5m wing span model (one eighth scale) took its maiden flight in 1987.[9] Based on the SHARP concept, the airplanes would circle slowly for many months at an operating altitude of 21 km and relay telecommunication signals within a diameter of 600 km. A high-power transmitter at 2.45 GHz was used to beam energy to the aircraft circling overhead. A custom printed-circuit array of dipole antennas with associated rectifying diodes coating the underside of the plane converted the microwave energy to direct current to power the electric motor.[9]

Fig. A.3.1 SHARP flight experiment and 1/8 model[10]

A.4 Japanese Activities

Fig. A.4.1 MINIX, the world-first MPT experiment in the ionosphere. ©RISH, Kyoto University

Based on a numerical estimation,[11] the MINIX (microwave ionosphere nonlinear interaction experiment) rocket experiment (Fig. A.4.1),[12] the world's first MPT experiment in the ionosphere, demonstrated power transmission from a daughter vehicle to a mother vehicle using a 2.45 GHz oven magnetron in 1983 and evaluated the nonlinear interaction of a strong microwave beam with the ionosphere experimentally[13], [14] and by computer simulations.[15]

The ISY-METS rocket experiment used a solid-state, phased-array transmitter to transfer power to a separate rectenna in space (joint experiment with USA).[16]

Fig. A.4.2. MILAX Airplane Experiment and Model Airplane. ©RISH, Kyoto University

A microwave-powered airplane whose beam power came from a solidstate phased array on a car at 2.41 GHz (MILAX, Fig. A.4.2) was demonstrated in 1992.[17] 2.45 GHz microwave power was beamed to a rectenna-equipped, helium-inflated airship in 1995. The output of the rectenna was 3kW. These applications were intended for a circling, high-altitude telecom platform in the stratosphere. A microwave-powered airship was demonstrated[18] as a study to apply MPT to a stratosphere platform for relaying communications. A proposal on satellite-satellite relay (power supplying satellite)[19] is another application.

Fig. A.4.3 Point-to-point microwave power transmission experiment in Japan. ©RISH, Kyoto University

A point-to-point microwave power transmission experiment (Fig. A.4.3) was performed by a parabolic transmitter antenna with a diameter of 3 m, and a rectangular rectenna array of 3.2 m × 3.6m for the receiving antenna. The distance between the transmitter and the receiver was 42 m. Received power was 0.75 kW for a transmitted power of 5 kW.[20] Recently MPT was proposed for wireless charging of electric motor vehicles.[21]

An ultra-small (0.4×0.4 mm^2) radio frequency identification (RFID) chip called μ-chip has been developed for use in a wide range of individual recognition applications. This is powered by 2.45 GHz microwave and the 128-bit memory data is read by a microwave signal with the same frequency.[22]

A.5 European Activities

Fig. A.5.1. Grand Bassin, Reunion, France

The opportunity to use a point-to-point wireless power transmission link to deliver 10 kW of electricity power to a small isolated village called Grand-Bassin is investigated in Reunion Island, France.[23] Grand-Bassin is a small, isolated mountain village located in the south of La Reunion (Fig. A.5.1). It is situated at the bottom of a 1 km high and 2 km wide canyon, with no road access. Currently, 40 people live permanently there during week days and more than 100 people on week ends.

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[1] W. C. Brown, The history of power transmission by radio waves, IEEE Trans. Microwave Theory and Techniques, MTT-32, pp.1230-1242, 1984.

[2] W. C. Brown, The history of wireless power transmission, Solar Energy, vol. 56, 3-21, 1996.

[3] P. E. Glaser, Power from the Sun: Its Future, Science, vol.162, pp.857-866, 1968.

[4] http://www.tfcbooks.com/images/articles/tower_sb.gif

[5] H. Matsumoto, Microwave power transmission from space and related nonlinear plasma effects, Radio Science Bulletin, no. 273, pp. 11-35, June, 1995.

[6] http://home.earthlink.net/~electronxlc/howworks.html

[7] R.M. Dickinson. Performance of a high-power, 2.388-GHz receiving array in wireless power transmission over 1.54 km, 1976 MTT-S Int. Microwave Symp. Digest, 139-141, 1976.

[8] James Benford, Flight and Spin of Microwave-driven Sails: First Experiments, Proc. Pulsed Power Plasma Science 2001, IEEE 01CH37251, 548, 2001

[9] J. J. Schlesak, A. Alden and T. Ohno, A microwave powered high altitude platform, IEEE MTT-S Int. Symp. Digest, 283-286, 1988.

[10] http://friendsofcrc.ca/SHARP/sharp.html

[11] Matsumoto, H., Numerical estimation of SPS microwave impact on ionospheric environment, Acta Astronautica, 9, 493-497, 1982.

[12] Matsumoto, H., N. Kaya, I. Kimura, S. Miyatake, M. Nagatomo, and T. Obayashi, MINIX Project toward the Solar Power Satellite---Rocket experiment of microwave energy transmission and associated nonlinear plasma physics in the ionosphere, ISAS Space Energy Symposium, 69-76, 1982.

[13] Kaya, N., H. Matsumoto, S. Miyatake, I. Kimura, M. Nagatomo and T. Obayashi, Nonlinear interaction of strong microwave beam with the ionosphere – MINIX Rocket Experiment," Space Power, Vol. 6, pp. 181-186, 1986.

[14] Nagatomo, M., N. Kaya and H. Matsumoto, Engineering aspect of the microwave ionosphere nonlinear interaction experiment (MINIX) with a sounding rocket, Acta Astronautica, 13, pp.23-29, 1986

[15] Matsumoto, H., and T. Kimura, Nonlinear excitation of electron cyclotron waves by a monochromatic strong microwave: Computer simulation analysis of the MINIX results, Space Power, vol.6, 187-191, 1986.

[16] Kaya, N., H. Matsumoto and R. Akiba, Rocket Experiment METS Microwave Energy Transmission in Space, Space Power, vol.11, no.3&4, pp.267-274, 1992.

[17] Matsumoto, H., et al., "MILAX Airplane Experiment and Model Airplane," 12th ISAS Space Energy Symposium, Tokyo, Japan, March 1993

[18] N. Kaya, S. Ida, Y. Fujino, and M. Fujita, "Transmitting antenna system for airship demonstration (ETHER), Space Energy and Transportation, vol.1, no.4, pp.237-245, 1996.

[19] Matsumoto, H., N. Kaya, S. Kinai, T. Fujiwara, and J. Kochiyama, A Feasibility study of power supplying satellite (PSS), Space Power, 12, 1-6, 1993.

[20] M. Shimokura, N. Kaya, N. Shinohara, and H, Matsumoito, Point-to-point microwave power transmission experiment, Trans. Institute of Electric Engineers Japan, vol.116-B, no.6, pp.648-653, 1996 (in Japanese).

[21] N. Shinohara and H, Matsumoto, wireless charging for electric motor vehicles, IEICE Trans. Electron., vol. J87-C, no.5, pp. 433-443, 2004 (in Japanese).

[22] M. Usami and M. Ohki, The μ-chip: an ultra-small 2,45 GHz RFID chip for ubiquitous recognition applications, IETCE Trans, Electronics, vol. E86-C, no. 4, 521-528, 2003.

[23] A. Celeste, P. Jeanty, and G Pignolet, Case study in Reunion island, Acta Astronautica, vol. 54, pp. 253-258, 2004.

Appendix B Various SPS Models

This appendix cites various SPS models from related home pages.

B.1 Glaser's SPS concept

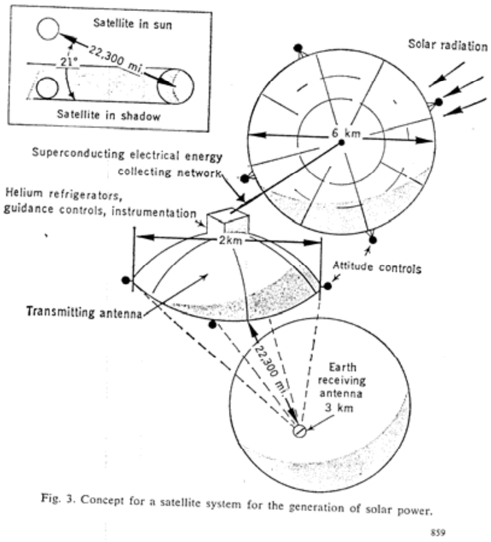


Fig. B.1.1 Glaser's SPS Concept[1.]

Peter Glaser proposed the concept[1] of Solar Power Satellite in *Science* in 1968 with two satellites in geostationary orbit. He used solar photovoltaic conversion to obtain DC and a klystron traveling-wave amplifier for DC-RF conversion as an example. For the 6-km diameter solar cells shown in the figure, about 6GW is obtained if their efficiency is assumed to be 15%. The solar cells of SPS are pointed at the Sun almost every day of the year. There are two periods of 42 days each during the Vernal and Autumnal Equinoxes when the Earth eclipses the satellite. The duration is a maximum of 72 minutes per day at midnight local time. Fortunately, this occurs at night when most industrial and residential users are inactive and during spring and fall, when demand for heat or air conditioning is lowest.

B.2 SPS2000[23]

SPS2000 is shaped like a triangular prism with length of 303 meters and sides of 336 meters (Fig. B.2.1). The prism axis is in the latitudinal direction, perpendicular to the direction of orbital motion. The power transmission antenna, spacetenna, is built on the bottom surface facing the Earth, and the other two surfaces are used to deploy the solar panels.

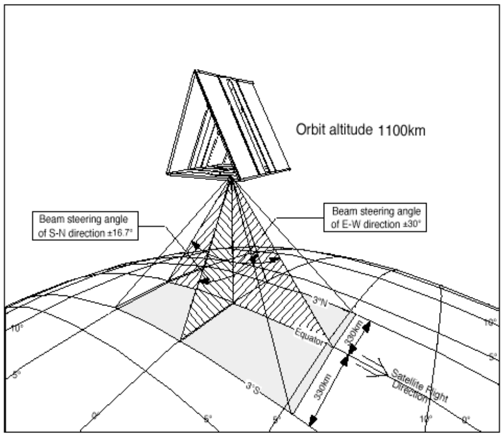


Figure B.2.1 General view of SPS2000.

SPS2000 is in an equatorial LEO at an altitude of 1100km. The choice of the orbit minimizes the transportation cost and the distance of power transmission from space. The spacetenna is constructed as a phased-array antenna. It directs a microwave power beam to the position where a pilot signal is transmitted from the ground-based segment of the power system, the rectenna. Therefore, the spacetenna has to be a huge phased-array antenna with a retrodirective beam control capability. Microwave circuits are therefore connected to each antenna element and driven by DC power generated in the huge solar panels. A frequency of 2.45 GHz is assigned to transmit power to the Earth. The ranges of the beam scan angle are ±30 degrees for the longitudinal direction and ±16.7 degrees for the latitudinal direction. Fig. B.2.1 also illustrates a scheme for microwave beam control and rectenna location. SPS2000 can serve exclusively the equatorial zone, especially benefiting geographically isolated lands in developing nations. The spacetenna has a square shape of 132 meters by 132 meters and is regularly filled with 1936 subarrays. The subarray is considered to be a unit of phase control and also a square shape whose edges are 3 meters. It contains 1320 cavity-backed slot antenna elements and DC-RF circuitry. Therefore, there will be about 2.6 million antenna elements in the spacetenna.

B.3 SolarDisc[4]

Summary The "SolarDisc" space solar power concept exploits a revolutionary paradigm shift to reduce the development and life cycle cost of a large satellite in geostationary orbit. In particular, the system concept involves an extensively axisymmetric, modular space segment that grows in geostationary Earth orbit (GEO), and can provide an early online capability at a reduced power level (Fig. B.3.1). A single satellite-ground receiver pair would be used; this pair can be sized according to the specific market, ranging from 1 GW to 10 GW in scale.

This concept, due to its extensive modularity, will entail relatively small individual system components that 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.

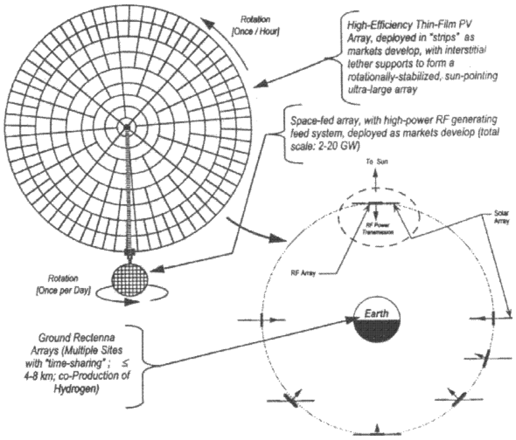


Fig. B.3.1 5 GW "SolarDisc" SPS System Concept

The "SolarDisc" concept is a single, large-scale GEO-based, RF-transmitting space solar power system. Each satellite resembles a large, Earth-pointing disc 3 to 6 km in diameter. This disc is continually Sun-pointing. The center of the disc is occupied by a hub that 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 km in diameter. The concept is assumed to transmit at 5.8 GHz from an operational GEO location, at a transmitted power level of 2 to 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 m in total diameter, and approximately 1.5 to 3.0 meters thick.

Sunlight-to-electrical power conversion is via a 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 2 to 4 meters wide. The collection system is intended to be always sun-facing (with orientation by angular momentum). Heat dissipation 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.

The nominal ground receiver for the SolarDisc concept is a 5 to 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., 10 to 20) could be served from a single SolarDisc SPS with time-phased power transmission. A ground-based energy storage system for primary power would not be required.

B.4 Abacus Reflector Configurations[5,6]

The 1.2-GW "Abacus" satellite configuration is depicted in Fig. B.4.1. This Abacus satellite is characterized by its simple configuration consisting of an inertially oriented, 3.2 × 3.2 km solar-array platform, a 500-m-diameter microwave beam transmitting antenna fixed to the platform, and a 500 × 700 m rotating reflector that tracks the Earth. It would be necessary to estimate effects of the finite size of the microwave reflector since its size is comparable to that of the antenna.

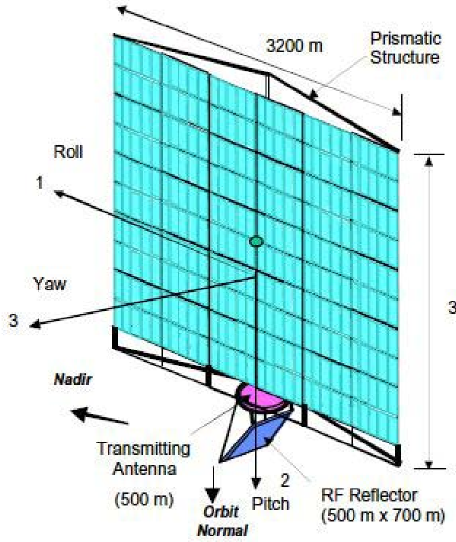


Figure B.4.1 Abacus Reflector

B.5 NEDO Model[7]

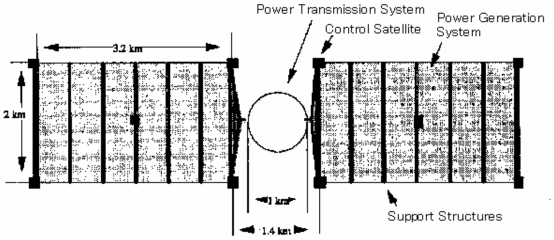


Figure B.5.1 NEDO SPS grand design

The New Energy Development Organization (NEDO), Mitsubishi Research Institute (MRI), and the Ministry of

Trade and Industry in Japan proposed a SPS model in 1994, which is basically revised from the NASA-DOE model introduced 20 years earlier. The generator uses Si crystal or amorphous solar cells, the transmitter uses solid state power amplifiers (SSPA) or klystrons at 2.45 GHz, and the antenna is a dipole antenna array. The output power is 1 GW on the ground. Rotary joints are used.

B.6 JAXA Models

The Japan Aerospace Exploration Agency (JAXA), formerly the National Administration of Space Development Agency (NASDA) in Japan studies the SPS conceptual and technical feasibility at different component levels of the SPS. JAXA proposed a 5.8GHz 1GW SPS model. Various configurations have been proposed, evaluated, and revised. The 2003 JAXA model is illustrated in Fig. B.6.1. The buoyancy can be used to fly the primary mirrors independently. Formation flying mirrors are used to eliminate the need for rotary joints. The whole system becomes mechanically more stable and reliable. The adoption of some wavelength selective films that could reduce unwanted light wavelengths is also considered. A Sandwich Concept was also proposed. In this concept, solar radiation is received on the front side, and microwave radiation is emitted on the back side. Some kind of joint module is required.

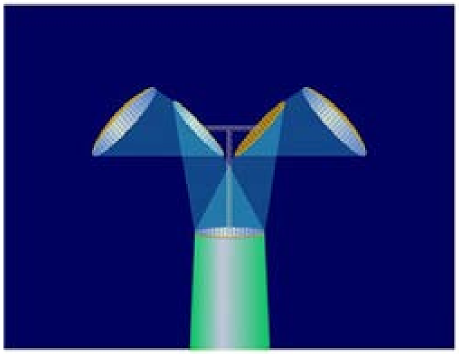
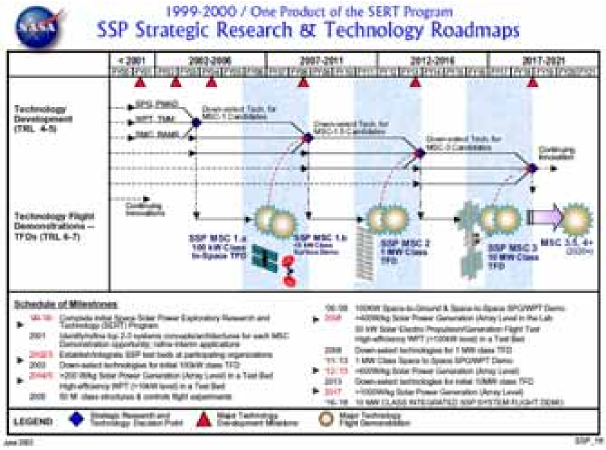


Figure B.6.1 JAXA 2003 Model

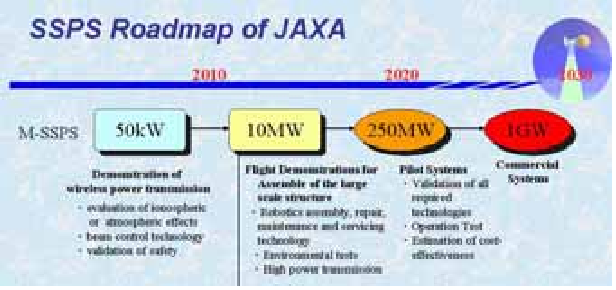
B.7 Roadmaps

The US NASA and JAXA are actively promoting SPS based on their roadmaps. As discussed in Chapter 5, each URSI commission can contribute to SPS in various aspects.



1999-2000 / One Product of the SERT Program

SSP Strategic Research & Technology Roadmaps



SSPS Roadmap of JAXA

Demonstration of wireless power transmission
- evaluation of ionospheric or atmospheric effects
- beam control technology
- validation of safety

Flight Demonstrations for Assemble of the large scale structure
- Robotics assembly, repair, maintenance and servicing technology
- Environmental tests
- High power transmission

Pilot Systems
- Validation of all required technologies
- Operation Test
- Estimation of cost-effectiveness

Commercial System

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[1] P. Glaser, *Science,* Vol. 162, 22 Nov. 1968.

[2] M Nagatomo, S Sasaki & Y Naruo, "Conceptual study of a solar power satellite, SPS 2000", Proc. ISTS, Paper No. ISTS-94-e-04, 1994; also at http://www.spacefuture.com/archive/conceptual_study_of_a_solar_power_satellite_sps_2000.shtml

[3] M Omiya & K Itoh, , "Development of a Functional System Model of the Solar Power Satellite, SPS2000", Proceedings of ISAP '96, Chiba, Japan; also at http://www.spacethemes.com/archive/development_of_a_functional_system_model_of_the_solar_power_satellite_sps2000.shtml

[4] J. C. Mankins, Acta Astronautica, Vol. 41, Nos. 4-10, 347-359, 1997

[5] http://flightprojects.msfc.nasa.gov/pdf_files/SSP_concepts.pdf

[6] http://techreports.larc.nasa.gov/ltrs/PDF/2001/aiaa/NASA-aiaa-2001-4273.pdf

[7] Research of SPS System (in Japanese), NEDO (New Energy Development Organization) /MRI (Mitsubishi Research Institute), Ministry of Trade and Industry, 1992, 1993, and 1994.

Appendix C: US Activities NASA SPACE SOLAR POWER ACTIVITIES: 1995-2005

Foreword

During the past decade, the US National Aeronautics and Space Administration (NASA) has conducted a series of studies and technology development efforts directed at the challenges of large-scale, affordable space solar power (SSP) systems. These efforts—which have addressed SSP for both space and terrestrial applications—have included the following:

- Fresh Look Study (1995-1997);
- SSP Concept Definition Study (1998);
- SSP Exploratory Research and Technology (SERT) program (1999-2001);
- Joint NASA-National Science Foundation SSP research and technology program (2001-2003); and,
- Relevant technology investments as part of the Exploration Systems Research and Technology (ESR&T) program (2004-2005).

For example, approximately thirty SSP systems concepts were examined during the Fresh Look Study. The most promising Solar Power Satellite (SPS) concept in this group appeared to be the "Sun Tower", a long (approximately 15 kilometer), gravity gradient stabilized configuration placed in either low Earth orbit (LEO) or geostationary Earth orbit (GEO). The Sun Tower concept incorporated active, solid state phased array for microwave wireless power transmission (WPT), as well as inflatable Fresnel lens concentrators for solar power generation. Variations of the Sun Tower and other concepts were analyzed during the SSP Concept Definition Study (CDS) and the SSP management team adopted several ongoing technology development projects across the agency. In 1999, the SSP Exploratory Research and Technology (SERT) effort involved a focused technology research and development (R&D) program, conducted systems analysis and integration studies, and developed concepts for SSP (and SPS) systems demonstrations. These efforts resulted in the development of an overall roadmap for SSP technology development, which was subsequently reviewed by the US National Research Council (NRC) in 2000. Later, the joint NASA-NSF research program (2001-2002) and the Exploration Research and Technology (ESR&T) programs (2004-2005) made significant investments in key space solar power systems technologies.

This summary of NASA's Space Solar Power (SSP) efforts—including SPS and related activities –during the past decade will address the following topics:

- Overview: What Is Space Solar Power? Why is SSP an Important Option?
- A Brief History Of Past US SPS & SSP Activities (1960s-1970s);
- Recent NASA Activities (1995-2005); and,
- Future Directions.

C.1 Overview

Large space solar power SSP systems have been under consideration by various groups for over 30 years. However, prior to the NASA's recent efforts, the last major studies in the US on the topic of large SSP concepts for terrestrial markets (i.e., "Solar Power Satellites" (SPS)) were conducted in the late 1970s. Following several years of effort (funded at a current year level of more than $50M), these SPS studies were canceled. Reasons included the very high technological risk and high up-front cost of space transportation and in-space infrastructures required to support large-scale construction activities in space. Technology advances in recent years have attracted new interest in large-scale space solar power satellite systems for transmission to terrestrial markets as a potential long-term clean energy option. These advances are important to the decision to reconsider space solar power, in particular since global energy demand continues to grow dramatically and environmental concerns over current-technology energy production continues to increase.

C.1.1 What is Space Solar Power?

The basic concept for space solar power is to collect solar energy in space and transfer it to the Earth for distribution as electrical power. This is the same basic concept that was studied in the 1970's as Solar Power Satellites (SPS). This latest series of studies produced a new look at the concept in light of the many new technologies that have been developed over the last 20–30 years. Today, as in the 1970's, there is a desire to find a global energy solution that is abundant, cost effective, environmentally friendly, and is consistent with national security considerations. SPS failed in the cost effectiveness category primarily due to the state of critical technologies and space infrastructures at that time. Today, SSP has seen significant development of many critical technologies and a technology development path has been identified that could lead to the construction of large power satellites in orbit during the next 20 years.

C.1.2 Why is Space Solar Power an Important Option?

During the next several decades global energy demand will grow dramatically and the management of environmental impacts resulting from growing power production will become an increasingly important international consideration. Demand for power in space is also likely to increase, driven by human exploration of the Moon and Mars, space science missions to the outer planets, and large-scale commercial development of low-Earth-orbit (LEO) and geostationary Earth orbit (GEO) space. All depend upon the availability of abundant, affordable power in space.

Global energy demand is growing due to increased power demands from developed countries, new emerging markets from undeveloped countries, and overall global population growth. Electricity is the fastest growing form of energy with continued growth projected for many years to come. It is interesting to note that after more than 100 years of steady development and growth of the electrical power industry, there are still 2 billion people (1/3 of the Earth's population) that are not hooked up to the grid.

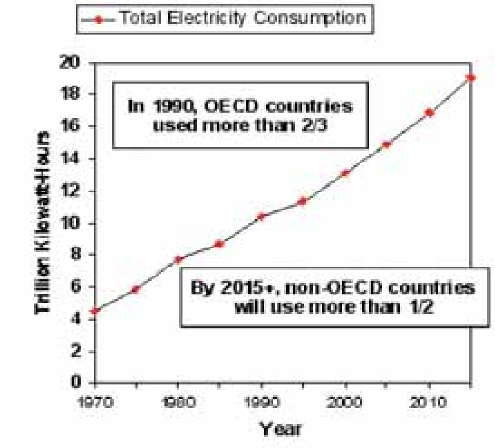

Figure C.1.1. The emerging global energy marketplace

Note 1. Each 0.01 trillion kilowatt-hours is equivalent to 3 million tons of coal per year.

Note 2. The OECD (Organization for Economic Cooperation and Development) represents the most developed nations in the world today.

The population worldwide is 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. Even in the US, where electrical demand has remained relatively stable for years, requirements now appear to be growing as a result of the increasing power needs of the electronic economy. The US Department of Energy (DOE) Energy Information Agency (EIA) recently projected that the worldwide use of electrical energy will approximately double in the next twenty years and will about double again in the twenty years that follow. In 1990, the nations of the Organization for Economic Cooperation and Development (OECD) used more than two-thirds of the world's electrical power production capacity. However, beginning in 2015, the DOE 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 the foreseeable future, see Figure C.1.1. However, electricity provides one of the cleanest forms of energy utilization available at the point of use. The problem is not in the use of electricity, but in the limited number of clean and safe methods available for electrical power generation.

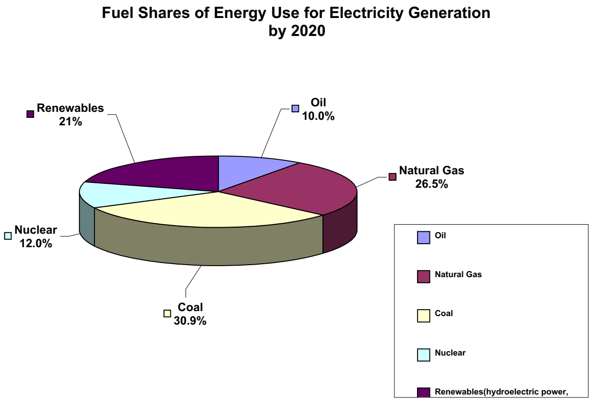

Figure C.1.2. Fuel sources for electrical energy production today and projected for 2020.

C.1.3 Key Findings from Recent SSP Activities.

After several years of structured research and the development of new concepts, technologies, and space infrastructures for space solar power development, the following key findings are note worthy.

- **Space Solar Power is technically feasible:** Multi-megawatt SSP systems for transferring power in space and to Earth appear viable. Questions remain concerning the economic viability of SSP to resolve the long term energy needs for a growing population and economies on Earth.
- **Technology development is needed:** A stable and structured research, technology development, and validation program over a period of perhaps 15 to 25 years will be required to enable SSP commercial development.
- **Space infrastructure development is needed:**

Supporting space infrastructures will be required for any large-scale construction activities in space. In particular there is a need for new low cost, highly reusable transportation systems to space and in space. It appears that without such systems, space solar power will not be economically viable.

- **Power beaming concerns have regulatory and technical solutions:** Environmental and safety concerns over wireless power transmission to Earth have solutions, but need international consensus. This is true for both microwave and laser beam power transmission approaches.
- **SSP could enable space development:** There are numerous applications for science, exploration, and commercial development of large power systems in space. In addition, the large-scale development of commercial SSP systems could bring down the cost of transportation systems and enable the large-scale development of many new space industries including space colonization.
- **International cooperation should be pursued:** Space solar power has the potential to be a global solution to a global energy production problem. As such its development should be pursued with international cooperation among governments and industries.

As a result, one of the key recommendations is that additional studies, technology developments, and appropriate demonstrations on Earth and in space be continued to prove the concepts developed during the space solar power activities of the past few years.

C.2 A Brief History of US SPS and SSP Activities (1960s-1970s)

The sun is one of the Earth's primary sources of natural energy. The challenge here is to find more efficient ways to collect this energy safely for use by industrially developed and developing countries around the world. In space, the solar intensity is about 30% more intense than the brightest sunlight on Earth due to the lack of atmospheric absorption. In addition, space based systems can significantly decrease the power loss effects of Earth based systems that experience day-night cycles, weather effects, and seasonable changes in the angle of solar flux incidence. All together, these effects can make space-based solar power generation anywhere from 6-times to more than 30-times more effective. These advantages were recognized early in the space program, which is the reason that nearly all Earth orbiting satellites use space solar power as their primary means of electrical power generation. On Earth, use of solar power generation is limited due to high cost and the inefficiencies caused by night cycles, cloud cover, and seasons.

In 1968, Dr. Peter Glaser of the Arthur D. Little Company, proposed the concept of exceptionally large "solar power satellites" (SPS) as one promising approach that might meet the challenge of satisfying terrestrial power needs in an environmentally friendly way. In this concept, solar energy is collected in a high orbit around the Earth, where sunlight is available almost continuously, and beamed as radio waves to receivers on the Earth. Studies were conducted primarily in the 1970's and 1990's as follows.

C.2.1 Solar Power Satellite Studies in the 1970s.

Various studies of Dr. Glaser's idea for solar power satellites were conducted during the 1970s, culminating in a major study led by the US Department of Energy (DOE) in 1976-1980 with support from NASA. This study resulted in the "1979 SPS Reference System". The 1979 SPS Reference System architecture entailed deploying a series of as many as 60 solar power satellites into geostationary Earth orbit (GEO). Each of these satellites was planned to provide dedicated, base load power of approximately 5 GW for a single large urban area, typically a city in the US. A large SPS – 5 km by 10 km in area and 0.5 km deep for a system delivering 5 GW to the ground – was to be assembled in space from large, compression-stabilized struts and joints. This platform was the fundamental building block of the concept. On these large platforms a host of very large discrete system elements were to 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 radio frequency (RF) power generation and transmission. Figure C.2.1 presents a conceptual overview of the 1979 Solar Power Satellite Reference System.

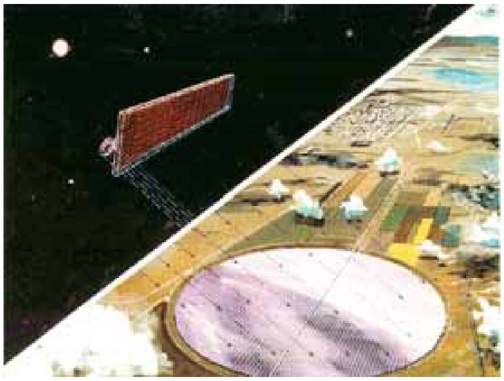

Figure C.2.1. The 1979 SPS Reference System concept showing the satellite in space and the ground receiver

These large platforms were to be assembled and deployed through the use of a massive, unique infrastructure. This infrastructure included a large (up to 250,000 kg payload class), fully reusable two-stage Earth-to-orbit (ETO) transportation system as well as massive construction facilities in low Earth orbit (LEO) and GEO that would have required hundreds of astronauts to work continuously in space for several decades. The financial impact of this deployment scheme was significant. Estimates projected that more than $280B (in 2000 dollars) would be required before the first commercial kilowatt-hour could be delivered. Recent studies suggest that updated estimates of the initial costs of this architecture would likely be significantly greater than those original estimates.

Ultimately, the US National Research Council (NRC) (part of the National Academy of Sciences (NAS)) and the former Congressional Office of Technology Assessment (OTA) concluded following reviews in 1980-1981 that although SPS were technically feasible, they were programmatically and economically unachievable at that time. As a result, US SPS activities were terminated in the early 1980's for reasons that included:

- The cost-to-first power > $280B ('00$) for the 1979 SPS Reference System was very high
- Massive initial government investment in infrastructure was required
- Too many dramatic advances in technology were needed
- SPS was viewed as largely a "US-only" proposition, with poor international involvement
- The new Administration (1980-1981) had other priorities
- The OTA and NRC criticized the proposed early deployment (1990s) scenario strongly
- The sense of public urgency concerning alternative energy sources was fading as oil prices plummeted in the early 1980s

Although the NRC recommended that related research should continue and that the issue of SSP viability should be revisited in about ten years, in fact all serious effort on solar power from space by the U.S. government ceased.

C.2.2 During The Interregnum: The 1980s and Early 1990s.

During the 1980s and early 1990s, grass roots interest in SSP continued in the US, while international interest and activities began to emerge. For example, the concept of basing SPS elements on the lunar surface was examined. Internationally, several key wireless power transmission (WPT) experiments were conducted in Japan and in Canada. One of these was the METS (Microwave Energy Transmission in Space) experiment, which in 1992 used a sounding rocket to investigate the nonlinear effects of a WPT beam in the space plasma environment. Another was the 1987 Canadian SHARP microwave transmission demonstration in which power was beamed to a small, un-piloted aircraft.

By the early 1990s, these developments came together in several expressions of international interest. One of these was the selection of SPS as the topic for a major study at the International Space University (ISU) summer session held in 1992 at Kitakyushu, Japan. Another was the creation in Japan of the concept of SPS-2000, a conceptual 10 MW LEO demonstration project for SPS. A third was a growing emphasis on SSP/SPS within the Space Power Symposium of the annual International Astronautical Congress (organized by the International Astronautical Federation (IAF) and the International Academy of Astronautics (IAA)). In addition, several international specialists' conferences were held on the subjects of SPS and wireless power transmission (WPT).

C.3 The NASA "Fresh Look Study" (1995-1997)

During 1995-1997, NASA pursued a "fresh look" at the topic of SSP in order to determine whether recent technology advances might enable an approach to SPS that could deliver energy into terrestrial markets at competitive prices. The "Fresh Look Study" concepts were challenged to accomplish market goals without major environmental drawbacks, and at a fraction of the initial investments projected for the 1979 SPS Reference System. Key findings of the study suggested that it might be appropriate to reopen the question of SSP viability; 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 called (at that time) for NASA to drive ETO costs down dramatically, Independent of SPS/SSP requirements;
- Important technical advances have been made

and new research and technology (R&T) avenues have been identified;

- Potential space applications of key technologies and systems have been identified for both NASA missions and commercial space markets; and,
- Strong opportunities appear to exist for international interest and involvement.

About 30 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 was the "SunTower" SPS. This concept would exploit a variety of innovative technologies and design approaches to achieve a potential breakthrough in establishing the technical and programmatic feasibility of initial commercial SSP operations. Capable of being deployed to various orbital altitudes and inclinations, including GEO, the SunTower concept involves little in-space infrastructure and requires no unique heavy lift launch vehicle (HLLV).

C.3.1 SunTower Concept

The SunTower SPS system concept emerged from NASA's 1995-1997 Fresh Look study and was further defined during the SERT program. The end-to-end scenario and details of the concept are as follows.

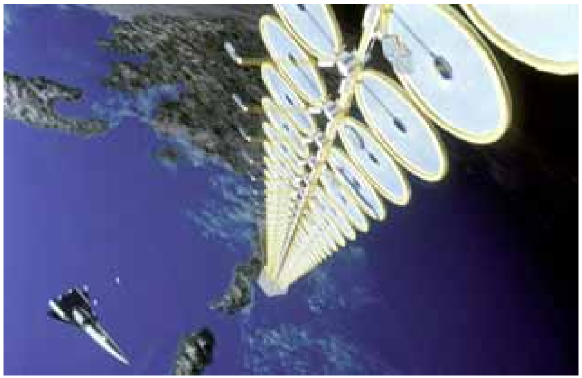

Figure C.3.1. The "SunTower" solar power satellite system concept

Each pair of circular units is part of an inflation deployable module with a net output of 2-3 MW of electrical power. Each module is delivered to orbit and connected to the top of the tower to form the long vertical structure of the SunTower. The large disc shaped wings concentrate and focus sunlight onto a photovoltaic array. Figure C.2.3.1 illustrates a reflector design for focusing sunlight onto the array, however Fresnel lens designs were also studied and considered feasible. As the tower orbits at a geostationary altitude, in sync with the rotation of the Earth, the disc reflectors rotate to track the sun. A known problem with this configuration is that the disc reflectors will begin to shadow each other as the tower approaches 12:00 noon and midnight. Options to avoid power loss during those times include using multiple SunTowers feeding common terrestrial sites, energy storage systems, and alternative terrestrial power production systems.

Today, the state of the art multi-bandgap solar arrays with concentrators have approached 30%-37% conversion efficiency. Still higher performance systems are expected in the next few years. In addition, the space demonstration of a large, 10 meter diameter inflatable structural system by NASA's Jet Propulsion Laboratory and the L'Garde Company suggest that very large, lightweight structural systems are possible.

Wireless power transmission (WPT) is used to beam energy from space to the Earth's surface. On the SPS, the power is transferred via power cabling from the array elements to a wireless power transmitter located at the Earth-facing end, or bottom, of the SunTower. In the SERT study the SunTower SPS is assumed to transmit at a frequency of 5.8 GHz from GEO, approximately 36,000 km altitude, at a power level of about 1200 MW received on the ground, (Figure C.3.1 illustrates a smaller system in LEO from the Fresh Look study). With technology advances, conversion efficiency from voltage to RF energy at the transmitter is projected to be greater than 80-85%. Beam-steering capability of approximately 6° would be required to address potential targets on the surface of the Earth ranging from about 50° North to 50° South. This range of potential ground sites includes many major developed countries and most of the developing countries around the globe — the continental United States, South America, southern Europe, Africa, the Middle East, Australia, China, and Japan. The transmitter array is an element-tiled plane that is essentially circular, approximately 500 meters in diameter. Each transmitting element is a hexagonal surface approximately 5 cm in diameter, which would be pre-integrated into sub-assemblies for final assembly on orbit.

The transmitted beam would transit the Earth's atmosphere with only minimal attenuation approximately 2-3% or less, and be received at a large rectifying antenna, called a "rectenna," on the Earth's surface and converted back into voltage for conditioning and distribution through the local power grid. With further technology development and validation, conversion efficiency for a rectenna at these frequencies should be approximately 80-85%. Also, past studies have found no measurable effects on living things resulting from microwave energy at the levels being discussed for SPS of 100-200 watts per square meter, which is only about 10-20% the energy contained in bright summer sunlight.

C.3.2 Solar Disc Concept

The Solar Disc SPS concept consists of a large spin-stabilized solar array in GEO that tracks the sun, with a de-spun phased array transmitter that tracks the Earth, see Figure C.3.2. The disc structure is designed with on-board robotic deployment systems that add to the disc diameter over time.

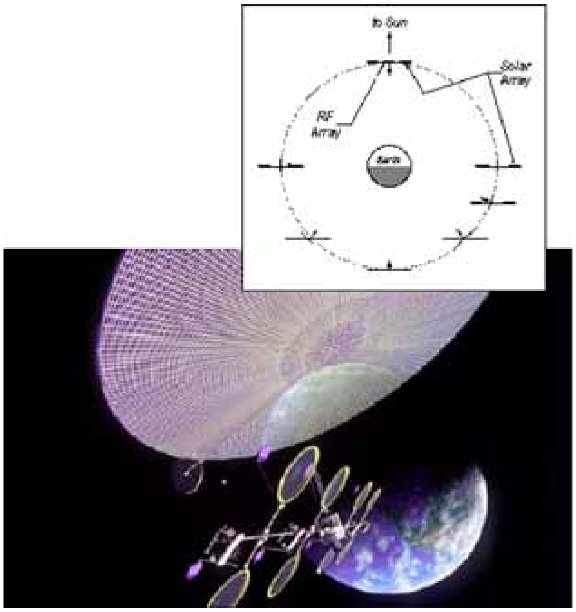

Figure C.3.2. Solar Disc concept for a space solar power satellite in geostationary orbit and a SunTower derived transfer vehicle

From GEO the transmitter could have ± 60 degrees latitude coverage at the Earth with about 5 GW electrical power output per SPS. With the entire array tracking the sun, there are no shadow effects, as was the concern noted for the SunTower configuration. At GEO there will be intermittent shadowing from the Earth, which would occur at 12:00 midnight. In general, this time has very low demand for power, which should be relatively easy to overcome through an additional SPS feeding the ground site, or ground power storage systems. Figure C.3.2 also shows a transfer vehicle derived from the SunTower concept. This vehicle utilizes solar energy to drive an electric propulsion system for raising Solar Disc components from LEO to GEO.

Apparent technical challenges associated with this Solar Disc concept include control systems that will keep the spin-stabilized disk pointing toward the sun, robotic assembly, and rotating slip rings that can accommodate the high power levels traveling from the solar array disk to the transmitter, which must remain fixed in its orientation toward Earth. Slip rings are also required for the SunTower concept, but since one is located at each disc reflector/array unit, the voltages are much smaller and thus less challenging technically.

C.3.3 Conclusions

In addition, during the Fresh Look Study, a number of intriguing potential non-SPS space program uses of the SunTower concept and related technologies began to emerge, including human exploration, space science and commercial space applications. As a result of these preliminary findings, fresh interest in SSP and SPS emerged within the US Congress as well as the US Office of Management and Budget (OMB).

C. 4 THE SSP Concept Definition Study (1998)

At the suggestion of the US Congress, in 1998 NASA conducted a follow on to the Fresh Look study, the SSP Concept Definition Study (CDS). The principal purpose of the SSP CDS was to validate, or invalidate, the results of the earlier effort. The objectives of the effort were to:

- Identify, define and analyze innovative system concepts, technologies, and infrastructures, including space transportation systems, 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 economic feasibility of such space solar power systems concepts
- 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
- 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, including the definition of technology development and demonstration roadmaps for critical SSP elements, considering performance objectives, resources and schedules, and possible "dual-purpose" applications (e.g.,

commercial development, science, exploration, and other government interests).

As a result of the 1998 SSP CDS effort, the principal findings of the Fresh Look study were validated. However, a number of the specific results were reassessed and detailed scenarios changed. For example, it was determined that earlier middle-Earth-orbit (MEO) options identified by the Fresh Look Study were not feasible. In addition, a family of ambitious R&T road maps was formulated and a notional technology investment portfolio was identified. Beginning in 1999 a new two-year activity was undertaken within the context of the CDS road maps to further test the viability of SSP, including the conduct of preliminary research and technology development in key areas.

C.5 THE SSP Exploratory Research & Technology (SERT) Program (1999-2000)

During 1999-2000, NASA conducted a SSP Exploratory Research and Technology (SERT) program. The goal of the SERT activity was to conduct preliminary studies and strategic technology research and development (R&D) across a wide range of areas to enable the future development of large, potentially multi-megawatt SSP systems and wireless power transmission for government missions and commercial markets for in-space and terrestrial space solar power. The objectives of the SERT program included:

- Refining 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 (including space transportation), and economics
- Conducting technology research, development and demonstration activities to produce "proof-of-concept" validation of critical SSP elements for both nearer and farther-term applications
- Initiating partnerships nationally and internationally that could be expanded, as appropriate, to pursue later SSP technology and applications (e.g., space science, SPS for terrestrial power, space colonization, etc.)

By accomplishing these objectives, the SERT Program sought to enable informed decisions regarding future SSP and related R&D investments by both NASA management and prospective external partners. In addition, the SERT program is intended to guide further definition of SSP and related technology road maps including performance objectives, resources and schedules, and multi-purpose applications, such as commercial markets, Earth and Space science, exploration, or other government missions.

The SERT program included both "in-house" and competitively procured activities, which were implemented through a portfolio of focused R&D investments, with maximum leveraging of existing resources inside and outside NASA, guided by systems studies. The portfolio consisted of three complementary elements:

- Systems Studies and Analysis – Analysis of SSP systems and architecture concepts, including space applications. Efforts have encompassed market and 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 major challenges with rapid analysis to identify promising systems concepts and establish technical viability.
- SSP Technology Demonstrations – Initial, small-scale demonstrations of key SSP concepts and components using nearer-term technologies, with an emphasis on enabling multi-purpose space or terrestrial applications of SSP and related systems and technologies.

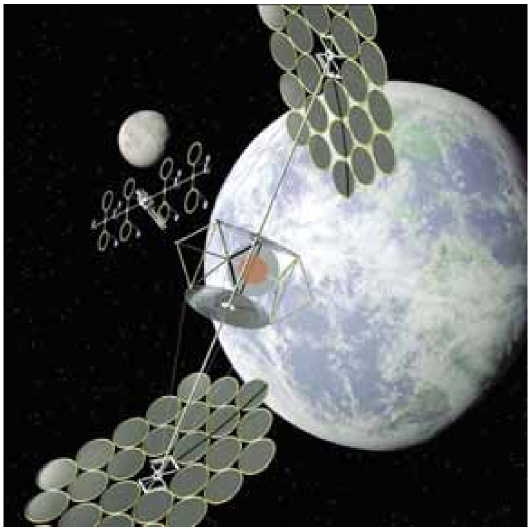

Figure C.5.1 An Integrated Symmetrical Concentrator SPS in GEO and a Solar Clipper Freighter

Figure C.5.1 depicts two examples of SSP systems concepts that were developed through the SERT program, the Integrated Symmetrical Concentrator (ISC) and the Solar Clipper. The ISC concept is a 1.2 GW (or greater) SPS system providing power for terrestrial markets and a variety of space facilities. The Solar Clipper concept is a solar electric propulsion (SEP) based space transfer vehicle (STV) that derives from the Sun Tower Concept mentioned previously.

Although depicted in this figure as a freighter, carrying parts to an ISC SPS system in GEO, the Solar Clipper may also be used to provide cargo transportation to—and power once located at—either the Moon or Mars.

Two concepts that were examined in some detail were the ISC (described above) and the “Abacus Reflector” concept.

C.5.1 Abacus Concept

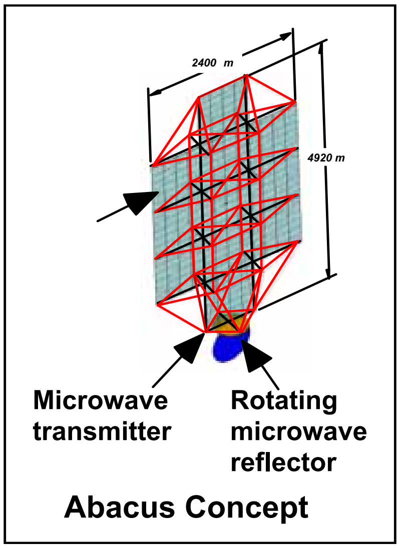

Figure C.5.2. The Abacus concept

The Abacus SPS concept utilizes a solar array and transmitter that track the sun. The transmitted microwave beam is reflected off of a rotating reflector to bend the beam and focus it on terrestrial receivers. Thus the rotation mechanism is placed after the major subsystems that collects the solar energy and generates the microwave power beam, avoiding the technical challenges associated with high voltages passing through large slip rings.

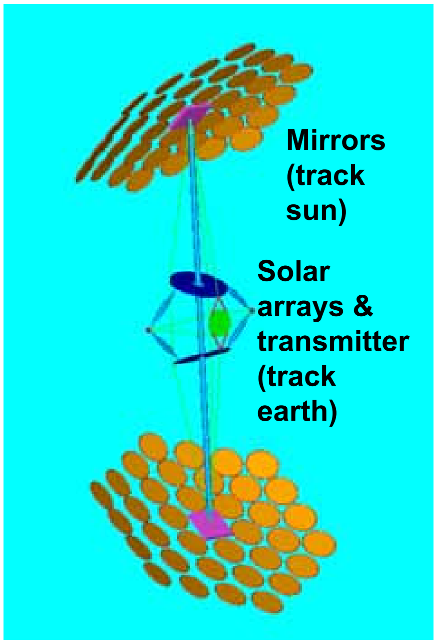

Figure C.5.3 The Integrated Symmetrical Concentrator concept concentrates sunlight and converts it to microwave or laser energy for transmission to Earth

C.5.2 Integrated Symmetrical Concentrator Concept

Another concept designed to avoid the slip ring problem is the Integrated Symmetrical Concentrator (ISC) concept, which utilizes mirrors to fold the sunlight through the required angles to an essentially fixed solar collector and transmitter that tracks the Earth. The mirrors in the ISC may be configured to concentrate the sunlight, thus reducing the size, weight, and cost of the solar array, and also provide tracking of the 23.5 degrees seasonal motion of the sun relative to the geo-synchronous SPS position. An additional benefit is the much shorter electrical power transmission distance between the solar arrays and the transmitter.

Many other variations on these basic concepts for collection and transmission of power to Earth were examined during the SERT activities resulting in a wide variety of technologies that were developed or identified as needed for potential future SSP systems.

C.5.3 Conclusion of the SERT Program

The SERT Program concluded in winter 2000 with a review by the NRC of the results of NASA’s efforts regarding Space Solar Power to date—with particular emphasis on a notional road map for strategic research and technology to realized large, affordable SSP systems in the future.

C.6 National Research Council (NRC) Review (2000-2001)

In early 2001 a committee for the National Research Council examined the SERT program's technical investment strategy and found that while the technical and economic challenges of providing space solar power for commercially competitive terrestrial electric power will require breakthrough advances in a number of technologies, the SERT program provided a credible plan for making progress toward this goal. The committee made a number of suggestions to improve the plan, which encompassed three main themes: 1) improving technical management processes; 2) sharpening the technology development focus; and 3) capitalizing on other work. In addition, the committee noted that even if the ultimate goal, to supply cost-competitive terrestrial electric power, is not attained, the technology investments proposed will have many collateral benefits for nearer-term, less-cost-sensitive space applications and for non-space use of technology advances.

Although the NRC committee neither advocated or discouraged SSP, it did recognized that significant changes have occurred since 1979 that might make it worthwhile for the United States to invest in either SSP or its component technologies. In particular it was noted that: improvements have been seen in efficiency of crystalline photovoltaic and thin-film solar cells; lighter-weight substrates and blankets have been developed and flown; a 65-kW solar array has been installed successfully on the International Space Station; wireless power transmission has been the subject of several terrestrial tests; robotics has shown substantial improvements in manipulators, machine vision systems, hand-eye coordination, task planning, and reasoning; advanced composites are in wider use; and, digital control systems are now state of the art. In addition to these encouraging advances, it was noted that public concerns about environmental degradation from current energy sources are more intense.

C.7 NASA-NSF_EPRI Research (2001-2003)

Following the completion of the NRC review, in order to broaden and strengthen US government investments in SSP research and technology, NASA worked with the National Science Foundation (NSF) to establish an inter-Agency partnership including NASA, NSF, and the Electric Power Research Institute (EPRI). These three organizations contributed funding and personnel to a broad agency announcement (BAA) with the purpose of supporting research in critical enabling technologies which will determine whether Space Solar Power (SSP) can someday become a viable cost-competitive technology for supplying large-scale base-load electric power worldwide. The solicitation emphasized (but was not restricted to) four special priority areas:

- Wireless power transmission,
- Computational intelligence for tele-autonomous robotic assembly,
- Environmental implications, and
- Power management and distribution.

This successful jointly-sponsored program—known as Joint Investigation of Enabling Technologies for SSP (JIETSSP)—resulted in about a dozen novel research and technology projects, ranging from intelligent cooperative robots, to the assembly of systems by means of self re-configurable robots, to microwave power beaming and advanced solar cells, to novel approaches using micro-channel cooling to solve SPS thermal management problems.

Contemporaneously with the completion of this jointly sponsored effort, NASA began to plan more aggressively for a renewed and strengthened program of human and robotic space exploration. These efforts resulted in a major new program, the Exploration Systems Research and Technology (ESR&T) program (discussed in the next section) that included significant investments in a range of technologies that are highly relevant to the challenges of solar power satellites.

C.8 Recent NASA Research and Development in SSP & Related Technologies (2004-2005)

On January 14, 2004 President Bush established a new policy and strategic direction for the U.S. civil space program—establishing human and robotic space exploration as it's primary goal, and setting clear and challenging goals and objectives. In response to this charge, the National Aeronautics and Space Administration (NASA) created a new Office of Exploration Systems (OExS)—subsequently the Exploration Systems Mission Directorate—at the Agency's headquarters and created or realigned several major programmatic budget themes. Recognizing that exploration must be "a journey and not a race…" NASA's program, and the President's FY 2005 budget included a substantial investment in identifying, developing and demonstrating new space technologies: the Exploration Systems Research & Technology (ESR&T) program. This effort addressed a small number long-lead, low technology readiness level (TRL) challenges, as well as a substantial focus on mid-term, moderate to high TRL challenges—with particular emphasis on those novel concepts and new technologies that might enable future exploration operations to be affordable, safe and effective in achieve mission objectives and science goals.

The ESR&T effort—focused on transformed space operations in the Earth's neighborhood—naturally encompassed many of the key technologies needed for future space solar power systems (including solar power satellites). The program was organized into three major efforts: the Advanced Space Technology Program (ASTP), the Technology Maturation Program (TMP), and the Innovative Partnerships Program (IPP). Within these areas, investments addressed the following SSP-relevant topics:

- Advanced Materials and Structural Concepts, including both Smart Materials and Structures, and Structures, Dynamics and Controls;
- Extreme Environment Electronics;
- Applications of "COTS" Computing in Space;
- Autonomy and Intelligent Onboard Operations;
- Intelligent Vehicle (System) Health Management (IVHM);
- Advanced Space Transportation, including Chemical and Electric Propulsion, and affordable aerobraking (including large, deployable aerobraking concepts);
- High-Efficiency / High-Power Solar Power Generation;
- Modular Power Management and Distribution;
- Thermal Management;
- Intelligent Modular Systems;
- In-Space Assembly, Maintenance and Servicing; and (for the longer term)
- In Situ Resource Utilization (focusing on lunar surface materials).

Through these investments, dramatic progress in a wide variety of the key technical topic areas identified in the 2000 NRC review of NASA's space solar power plans is being made. (R&D for the first year of these challenging new projects is still in progress.)

C.9 Summary and Conclusions

From the systems integration activities conducted during the past decade, there have emerged numerous general findings and issues relevant not only to the specific concept under study, but also to the overall concept of space solar power generation for Earth. Some of the key findings are summarized as follows.

C.9.1 General Findings

System Requirements: Insufficient attention has been given to the system requirements and interfaces for a fleet of SSP spacecraft; e.g., safety control for the many multiple beams, the Earth electrical grid interfaces for gigawatt-level beam outages, and fast-acting energy storage and switching. The primary requirements issues should be defined and generic paths formulated to resolve them.

Operations architecture: The SPS is in competition with ground systems that have lifetimes of 50+ years. To be cost competitive, the SPS must operate reliably and at a minimal operational cost for a long time. This aspect of the SSP concept has not yet been addressed adequately.

Systems Analysis: Coordinated systems analysis of the various SSP concepts, the model system categories, and the demonstration mission designs have been extremely effective in helping guide and systematize the course of SSP research. Demonstration mission designs for the following SSP system concepts have been especially useful: gravity-gradient abacus derived from the SunTower configuration; reflector abacus; integrated symmetrical concentrator; and Halo orbit concept. The system analyses for these concepts included power train efficiency analysis; PMAD design concepts; launch packaging and deployment concepts for the solar arrays, reflectors, PMAD systems, and transmitters; robot assembly procedures; and full mass and cost breakdowns, plus a number of sensitivity studies.

Various designs for early demonstration projects included space-station free-flyer demos using the Spartan payload, a cargo delivery and power beaming vehicle, a low-Earth-orbit propellant conversion and cryogenic storage facility, a Mars transfer vehicle, a lunar crater ice-mining mission, a high-power commercial communication satellite, a Mars cargo mission, a Mars human-crew sprint mission, and various laser power transmission applications both large and small scale. As a result, a significant number of findings and issues were discovered through the detailed conduct of the integration and analysis of these various system concepts. These findings included the following.

- Solar cell and WPT efficiencies are a major mass, size, and cost driver.
- Solar-thermal power generation using a Brayton (gas-turbine) cycle offers the highest overall system efficiency followed by Q-dot PV systems.
- Increasing power density via the Stretched Lens Array (SLA) concentrators also has a major effect on mass and size reduction of PV-based power generation concepts.
- Technology for the small assembly robots, and

especially control issues for multiple coordinated robot families, is highly immature, and imposes a major technical risk.

- The high voltage required for microwave-system PMAD poses significant technical risk. Minimum PMAD configurations, motivated by large PMAD masses, have been identified
- Structural and PMAD mass of the SunTower-derived concepts has grown significantly since the 1998 Concept Definition Study. However, the new Integrated Symmetrical Concentrator concept reduces both structural and PMAD mass significantly. (Still better concepts seem likely to emerge during the coming several years.)
- Most promising RF microwave-system configurations to date are:

  <u>ISC:</u> lightest, most cost-effective, but requiring advanced PV and thermal management technology

  <u>Abacus Reflector:</u> modular assembly/maintenance, moderate energy cost, but reflector issues exist

  <u>SunTower:</u> easiest assembly and control, but highest energy cost due to shadowing
- The filtering required to preclude interference with communications satellites will be very costly in overall system efficiency, and will impact both mass and cost.
- There is little cost sensitivity among the three microwave power transmission devices (klystrons, magnetrons, or phased-array solid-state devices).
- Reflector flatness is a key factor in the ISC and transmitter-reflector configurations.
- PMAD systems employing ac are much lighter and more efficient than those employing dc.
- New configurations that eliminate power-conducting slip rings have been identified
- Alternative options include Halo constellations for both RF and laser WPT, solar dynamic configurations, and SunTower derivatives, as well as others
- Distributed laser-based WPT configurations are very promising
- Orbit transfer propulsion, solar power generation, PMAD and ground systems are the primary contributors to SSP delivered energy costs.
- Configurations delivering 1.2GW have an energy cost range of 17¢-32¢/kWhr, which can be reduced by approximately 1¢-2¢/kWhr by delivering higher power densities per satellite
- Under current pricing assumptions, self-transfer of SSP payloads from LEO to GEO is more cost-effective than a purchased space transportation service.
- Advanced technology SEP systems offer an excellent non-nuclear transportation alternative for HEDS missions to the Moon and Mars.
- SSP technology can enable space exploration and development in the near term
- Advancements in SSP-related technologies produce wide-ranging performance and cost benefits for commercial, scientific and exploratory space applications.
- Microwave SSP systems are relatively efficient, and can beam power through clouds and light rain
- RF spectral constraints on SSP side-lobes and grating-lobes imposed by the ITU result in design and filtering requirements that lead to reduced efficiency and larger, more costly systems.
- Laser SSP systems allow smooth transition from SSP to conventional power, offer more useful space applications, and open up new architecture options that have not been sufficiently explored in the SERT program.
- Laser and microwave SSP systems may have differing design drivers, and because of their potential, laser based systems deserve comparable consideration in future studies.
- Significant advances in reducing the cost and increasing the launch rates for both ETO and In-space transportation are necessary to realize SSP
- To deliver cost-effective power from space, manufacturing and testing processes for space systems must become efficient and capable of managing huge volumes, and further provide significant high production cost improvements.

The focus on laser technologies for wireless power transmission began late in the SERT program due to initial concerns over lasers being used or publicly construed as weapons technology. Further analysis indicated that design concepts and power levels could be developed that are safe, and that laser systems open up many other options that appear to have a positive benefit to the overall SSP architecture.

Three topics of particular importance conclude this paper: environmental factors and concerns, prospective synergistic applications of SSP technology areas, and future directions for technology development and demonstration efforts.

C.9.2 Environmental Issues

Every advance in technology is not without concerns of its impact on the environment and related safety issues. Previous generations have been less concerned about these issues, which has led to mining of raw materials and production systems that have overtime been identified as detrimental to the environment in general, and in some cases harmful to human life in particular. The SERT activities included consideration of SSP development and operation in terms of potential environmental and safety factors, and the impact alternative approaches will likely have if power production continues using the conventional sources available today.

C.9.2.1 Environmental and Safety Factors.

Environmental and safety factors (ESF), including both in-space and terrestrial regimes, are very important to the programmatic viability of large-scale SSP systems. Several SERT technology activities incorporated ESF related R&D. In addition, SERT ESF efforts involved further refinement of space environmental data and issues, consideration of environmental and safety factors as they involve long-term applications of SSP to terrestrial markets, and related issues. This included the possible effects of SSP system launch, space environmental impacts on SSP systems, and possible effects of wireless power transmission from space-to-ground on the Earth's environment.

The 1979 SPS study used RF transmissions to earth from solar power satellites. Early technical estimates required large ground rectennas, about 35,000 acres (~55 mi^2) of ellipsoid, including a buffer zone. They also envisioned a network of about 60 such rectennas. More recent technical estimates suggest ~2 mi diameter rectennas (~3-4mi^2). Land use issues to be concerned about could include ecosystem disruption and habitat loss, human population dislocation, and infrastructure support concerns.

The energy transmitted to Earth from a SPS in orbit will be by either laser or microwave transmission. Collection facilities similar to solar arrays for lasers and rectennas for microwaves then feed the electricity to the electric grid. Power level intensities for the center-of-beam are 100-200 watts/m^2 with platforms ultimately producing 1-3 GW each. The primary issue is the potential health risk from exposure to these energy fields at the receiver sites where energy levels may be 10 to 20 percent higher than solar radiation in a beam potentially a kilometer or more in diameter.

For microwave systems the rectenna designs vary, but a common model cites a center energy intensity of about 23 mW/cm^2 dropping off to about 0.1mW/cm^{2}at the edge. The average beam intensity would roughly be about 10 times less than sunlight at the ground. However, at the transmitting antenna in GEO, the beam intensity will be about 2200mW/cm^2. For comparison, it should be noted that average solar power densities on Earth from the sun are about 100-200mW/cm^2.

The United States and Western Europe have adopted 10mW/cm^2 as a guide for both public and occupational exposure to continuous man-made microwave radiation. Canada adopted a limit of one mW/cm^2 for public exposure. The former Soviet Union and Eastern European countries allow 0.001mW/cm^2 for occupational exposure. Also, the Eastern European countries have established exposure standards based on non-thermal effects of microwave radiation, derived from allegations of possible behavioral impacts.

The exposure standards for the United States and Western Europe are primarily guided by risk avoidance of thermal biological effects. Exposure criteria are usually based on thresholds for biological damage at a specific absorption rate (SAR) of 4000mW/kg averaged over the whole body Limits are set at 400mW/kg for controlled or occupational exposure and 80mW/kg for uncontrolled or general population exposure, respectively, and for partial-body (localized SAR), such as might occur in the head of a user of a hand-held cellular telephone.

Although there is no evidence of negative environmental impacts from either microwave or laser approaches to wireless power transmission at the power intensities considered by recent SSP studies, environmental and safety factors should be given careful consideration and further study. The possible environmental benefits of power from space should also be further assessed in comparison with the growing long-term environmental impacts of power generation using fossil fuels.

C.9.3 Synergistic Applications

In addition to the need for affordable, abundant power on Earth, there is also a similar need in space. Recent studies suggest a wide range of important potential space applications of SSP technology and systems concepts in three important areas: space science, space exploration, and commercial developments in space.

C.9.3.1 Space Science

In the area of space science, an immediate application emerges in the form of higher power, lower cost and longer lived solar-electric power and propulsion systems. Many ambitious potential space science mission goals depend upon high-performance propulsion such as could be achieved with solar-electric power and propulsion systems in the 50kW-and-higher power class. Some science and robotic space exploration mission possibilities that might be interesting for integration with SSP studies are as follows:

- **Multi-asteroid sample return:** It would seem that developments in SSP or laser-solar propulsion would be interesting to the science community if they enabled a single mission to visit a significant number of belt asteroids in a 2-5 year period, collecting samples for return to Earth. Current technology is able to fly asteroid rendezvous missions, but eventually the prize is to sample a significant number of asteroids.
- **Asteroid/comet analysis:** Robotic spacecraft could determine the chemical content of comets and asteroids on rendezvous missions, enabled by solar-electric propulsion, by using deep-penetration imaging radar and by beaming laser and/or microwave power down to the surface to vaporize material for spectrographic analysis.
- **In-space transportation:** Solar electric propulsion (SEP) is clearly applicable to a wide range of science missions and human exploration missions, discussed later. Also, WPT offers opportunities for sensor deployment via laser sails, laser-thermal propulsion, and laser-electric propulsion.
- **International Space Station:** Replacement of ISS solar arrays for pre-planned performance improvements could employ advanced technologies developed for SSP, and wireless power transmission (WPT) could be used for co-orbiting experiment platforms requiring ultra-high vacuums and levels of microgravity unattainable in the inhabited station itself. Such platforms would experience much lower drag than self-powered ones, because rectennas require much smaller areas than equal-power solar arrays.
- **Radar and radiometer mappers:** High-power planetary probes equipped with 100-200 kW SEP systems could utilize their power sources to conduct radar mapping missions of planetary surfaces, enabling subsurface exploration and resource detection. This would be particularly valuable in support of asteroid missions and future missions to the Moon, Mars, and the moons of Jupiter and Saturn. High-power radiometers could also enable much more comprehensive scientific studies of planetary environments.
- **Rovers:** Deployment of large numbers of small rovers on lunar and planetary surfaces could be enabled by WPT from a central source on the planet or from an orbital location. Such rovers could be used for exploration, collecting scientific data, prospecting, and, eventually, in-situ resource recovery.
- **Lunar observatories:** The Moon has been considered for four decades as an ideal location for optical and radio telescopes, because of the major reduction in electromagnetic radiation clutter as compared to Earth-based or Earth-orbital systems. Support of such observatories could be implemented by mobile rovers powered by WPT from central lunar sites or from orbital locations. Large modular telescopes, both fixed and mobile, that are spread over hectares of lunar-surface area (e.g., interferometers), could also utilize WPT for their power requirements.
- **Space-based telescopes:** Large modular telescopes in heliocentric orbits several astronomical units from the Sun offer benefits to astronomers unobtainable within the inner solar system (e.g., absence of zodiacal dust, which interferes with infrared observations). Such telescopes could use several key SSP technologies; including high-power SEP for their deployment, WPT for on-board power and station keeping of the modular telescope elements, large thin-film structures, and inflatable structures.
- **Networked sensor systems:** Hundreds of tiny sensors, powered by half-wave dipoles, receiving power from a “mother” satellite equipped with WPT transmission capability, can conduct detailed four-dimensional surveys of interplanetary and other space regions, and possibly holographic interferometer studies of stellar and other phenomena.
- **Interstellar probes:** There is great potential commonality between the ultra-low-mass “gossamer” materials and structural concepts required for SSP and those required for the

solar sails that might be used for interplanetary and interstellar probes. Moreover, the enormous power requirements for such probes could be met by WPT (lasers) powered by large orbiting SSP systems. In addition, the new carbon-fiber sail materials, which have experimentally demonstrated sail accelerations from 1 to 10g without failure, are of particular interest here.

In the very far term, the ambitious goal of sending robotic probes beyond our solar system, first to the Kuiper belt, then to the Oort Cloud and beyond, will only be viable if extraordinarily low-cost and high-performance propulsion systems can be developed. SSP technologies and system concepts, in particular wireless power transmission, offer one important path to such future missions.

C.9.3.2 Space Exploration

SSP technologies are also broadly applicable to a number of system and architecture options for the future human and robotic exploration of space. For example, the largest solar arrays ever deployed in space were attached to the International Space Station in low Earth orbit in December 2000. Advanced solar arrays could be used in evolutionary upgrades of the ISS, maintaining power levels while reducing array sizes and re-boost propellant logistics costs. Solar-electric power and propulsion systems in the 100-300kW-class may be used to affordably transfer exploration systems of 10-50t from low-Earth orbit to other locations of interest in the Earth's neighborhood, such as the Earth-Moon or Sun-Earth Libration points. Systems in the 1MW class have been identified as an important option for transporting large payloads of 100t or more from low-Earth orbit to high-Earth orbit as one phase in a non-nuclear approach to human interplanetary missions. In addition, systems in the 1-10MW-class may enable reusable interplanetary transports for cargo (and perhaps people). Once at a target destination, for example in areosynchronous Mars orbit, such interplanetary transports could also serve as power stations, beaming abundant and affordable power down from space to provide non-nuclear energy to planetary or lunar surface outposts and operations. Figure C.9.1 illustrates one such concept, the Solar Clipper, derived from the "SunTower" SPS concept described earlier.

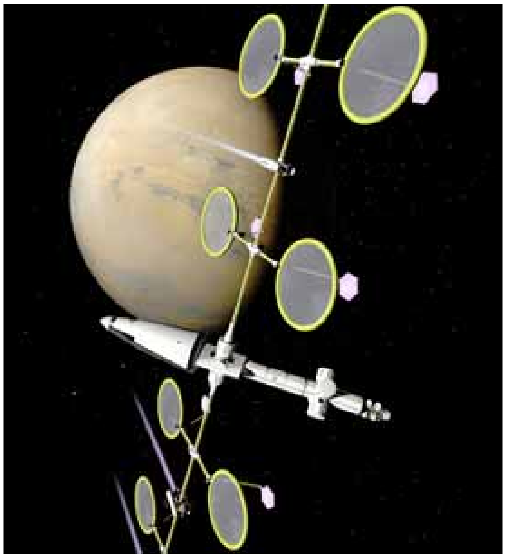

Figure C.9.1. The "Solar Clipper" interplanetary transportation system concept

C.9.3.3 Commercial Space Development

Finally, in prospective commercial development of space markets, several potential applications have been identified. For example, geostationary Earth orbit (GEO) based communications satellites have grown substantially in size during the past 20 years. The most recently deployed systems have approached a level of 20kW operating power. Preliminary studies, based on current market projections suggest that, during the next 10-20 years, mega-communications satellites in the 100kW-class located in GEO could become economically viable. Studies carried out in the SERT program suggest that the barriers to such growth, principally existing launch vehicle payload size constraints, might be surmounted through the application of SSP technologies and concepts. Several other potential commercial space applications have also been identified, ranging from the concept of a power plug in space for space-to-space power beaming system, to on-board power for future commercial space business parks, see Figure 9.2, and propellant depots using SSP technology for in space propellant production processing.

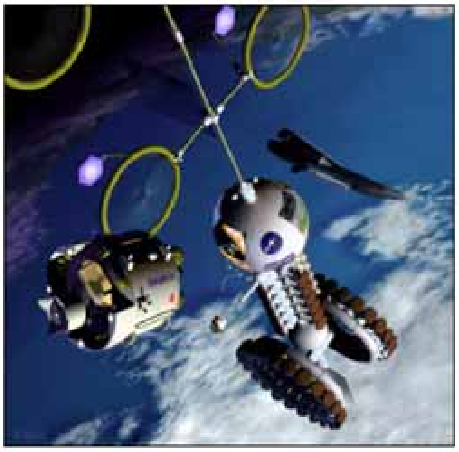

Figure C.9.2. A Space Business Park concept for a multipurpose commercial space station with artificial-g spinning ring, zero-g staterooms, and an inflatable arena sphere

Other space development applications for space solar power technologies have dual purposes for commercial applications as well as science, exploration and military applications. These include the following.

- **Micro satellites:** There could be applications of beamed power for very small military surveillance satellites. If they are not required to carry large photovoltaic arrays, they may be more difficult to detect from the ground or by interceptor satellites. Also, small commercial satellites could be battery powered with periodic charging from remote power sources.
- **Radar satellites:** The very high power enabled by advanced SSP-type solar arrays could provide the basis for 100-200-kW radar sensors, which have been under consideration by the military services for several decades but have to date been deemed infeasible due to their excessive power requirements.
- **Maneuverability:** Electric propulsion via WPT could enable significant increases in maneuvering reserves, using ion or plasma propulsion for long-term orbit changes and arcjets or laser propulsion for higher-thrust requirements.
- **Satellite servicing:** Maneuverable satellites could be refueled and onboard sensors and information-processing systems could be upgraded or replaced using beam-powered robot servicing spacecraft.
- **Orbital debris removal:** Orbital debris removal could be a good demonstration mission for power beaming. In this application, a small spacecraft would be maneuvered, using beamed energy, to rendezvous and grapple with a piece of space junk, possibly lowering its orbit and returning the spacecraft to the Station or Shuttle. Space-based lasers could also be used to vaporize smaller debris or to redirect the orbits of larger pieces to atmospheric reentry trajectories.
- **Planetary defense:** Space-based planetary defense system architectures, for protection against large asteroid or comet strikes would require substantial amounts of power distributed among a large satellite constellation. A central SSP power station using WPT could meet that need.
- **Power for communication satellites:** Satellite power demand is on the increase, with both Lockheed Martin's 20.20 bus and Hughes new HS 702+ series rated at 25 kW. Further increases are certain, and there will be a crossover point at which onboard power supply, with its inherent thermal-energy dissipation problems, maneuverability limitations, and the requirement for ever larger, and more costly launch vehicles will become more expensive than beamed power from dedicated space-based power plants. The use of high levels of WPT for electric propulsion, both for satellite orbit insertion and north-south station keeping, is an extra dividend. Power beamed by WPT during eclipse periods could also significantly reduce battery storage mass. Such power plants could serve as economically viable demonstrations of larger SSP systems.
- **High power for the International Space Station:** Supplementary power beamed to the ISS could extend the scope and breadth of commercially oriented research and experiments, allow additional crew members, and increase the station's self-sufficiency.
- **High-efficiency solar arrays:** During the transition to off-board beamed power for commercial satellites, improvements in specific mass resulting from SSP technology development in both power and structures technologies could provide significant power growth (e.g., perhaps up to 35 – 50 kW) in conventional communication satellite power supplies.
- **Power/communications satellites:** Dual-purpose satellites, which both deliver

power to terrestrial grids and provide high-power communications services (e.g., at the 1 – 50 MW level) could provide an interesting commercial prospect in the mid-term, as communications power demand continues to grow. One issue that would need to be addressed for this dual-use application is the spectrum spreading associated with carrying the modulation needed for high-data-rate communications, which would be incompatible with the ITU and the FCC desires to filter WPT microwave beams to reduce carrier noise and harmonics.

- **Long-term development:** Far-term opportunities for space-based industrial parks, space-based manufacturing plants using non-terrestrial materials (lunar and asteroid), tourist facilities, and space colonies, will all require substantial electric power, which could be supplied by local SSP systems or via WPT from orbital power-supply depots.
- Other applications relevant to space development, but directly beneficial to terrestrial industries are as follows.
- **Robotic aerial vehicles:** Power supply for the free-flight propulsion of aerial vehicles via WPT has already been demonstrated in Canada (SHARP) and Japan (MILAX and HALROP/ETHER). Potential applications are surveillance with indefinite loiter capability, meteorological observations, field communications between line-of-sight-obstructed mobile stations, measurement of high-altitude Sun-Earth interactions, upper-atmosphere sampling without contamination by onboard combustion, pollution monitoring and other Earth-observation applications, etc.
- **Offshore oil platforms:** Flaring of natural gas is a waste process that is inherent to offshore oil production, because the cost of either storing the gas for shipment to shore or of building a gas pipeline is prohibitive. However, the prospect for converting the gas energy to electricity via an onboard gas-turbine plant and transmitting the power to land via WPT offers an interesting prospect for cost recovery of the considerable intrinsic value of the gas.
- **Tornado mitigation:** Tornados form within severe thunderstorms, beginning as “meso-cyclones” in the cold downdraft regions of such storms. Thermal energy from a space-based power satellite could be used to heat the raindrops in these cold downdraft meso-cyclones, thereby disrupting the tornado genesis process. Numerical simulations suggest that tornado formation in the smaller meso-cyclones could be prevented by delivering 0.5-10 GW of beamed power into the cold downdraft. Absorption of energy by the large raindrops associated with such storms would be effective in the Ku–V band of frequencies (12 – 60 GHz).

There appear to be many synergistic applications of space solar power satellites, SSP derived systems, and associated technologies. These applications were found to be beneficial to many future NASA missions as well as commercial space development and terrestrial applications other than commercial base power production.

C.9.4 Future Directions

A broad-based NASA, industry, and university team, in response to strong external interest in the idea of solar power from space, conducted the a series of studies and R&D efforts during 1995-2003, and with SSP-relevant R&D continuing during 2004-2005. These efforts resulted in important improvements at all levels in SSP concepts, ranging from architectures to systems to technologies. More detailed definition of key system elements has yielded better understanding of masses (and costs) than earlier estimates. Overall, NASA, industry and university studies during the past ten years suggest that the use of new technologies and innovative systems concepts may lead to large scale space solar power for a variety of space applications that are far more viable now than has been previously believed. In addition, the application of very large-scale SSP for terrestrial markets may become viable during the next 20-30 years.

Although hydrocarbon fuels dominate current world energy supplies, 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 will be available for large scale development and deployment. Solar power systems are philosophically attractive as an alternative for base load power supplies due to the essentially infinite availability of energy. However, the financial realities of base load 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.

In summary, key recommendations for future activity includes:

- Concept definition studies for new innovative SSP systems should continue. There are numerous SSP concepts that have been defined and could be viable. Future technology development will impact the viability of these concepts and generate new ideas. New ideas will generate innovations in new technologies.
- Detailed economic and market analysis will help determine the viability of any SSP system. However, pure economics is not the only issue when faced with the alternative approach of continued use of fossil fuels that produce pollutants.
- Continued technology development is needed to generate more efficient SSP systems. These same technologies have numerous applications to terrestrial products and services.
- Future development of SSP systems can be done through a wide variety of demonstration missions that can benefit commercial space, space exploration, and space science missions.
- Supporting infrastructures for space development in general, and low cost space t

tion in particular are critical to the success of future SSP development. Earth to orbit and in-space transportation cost must be significantly reduced over the next 10 to 20 years.

- Although there appear to be no major environmental issues, this must be studied on a US and international level to gain public confidence that SSP wireless power transmission is safe. Also, global issues in the increased use of fossil fuels and their impact should be part of any comparable assessment.
- The long-term development of SSP appears to have many beneficial applications to space development in general, including substantial benefits to science, human exploration, commercial development, and defense.
- International participation in the development of SSP programs is critical to success since the SSP system itself is capable of providing power to any local on Earth. Many under developed regions could benefit economically from SSP development, which could ultimately help raise the world's standard of living.

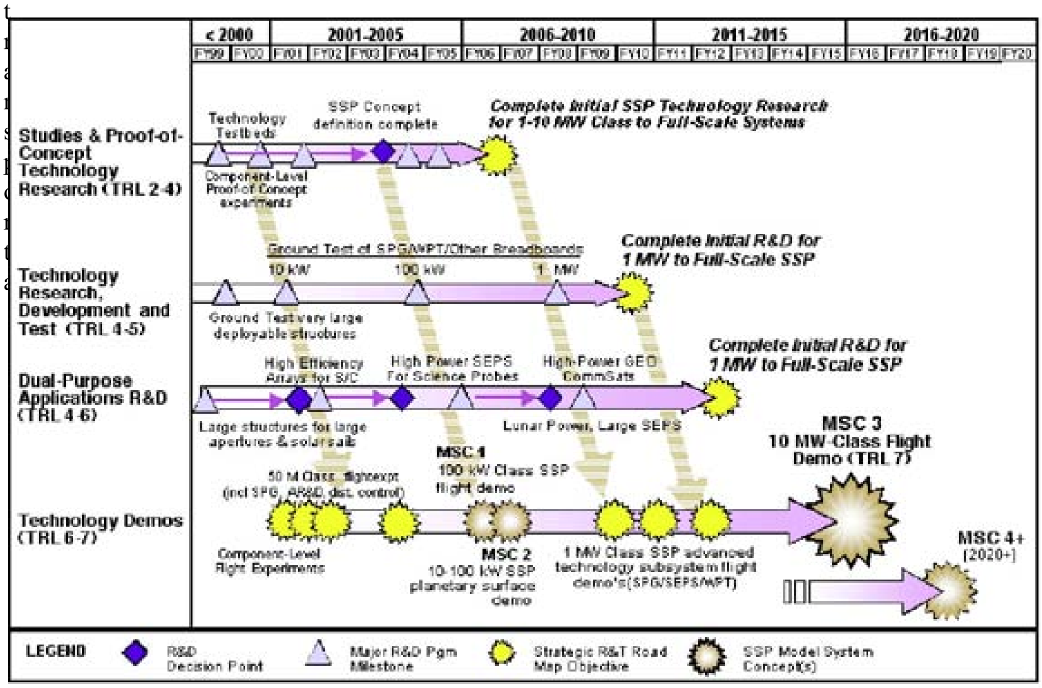

Figure C.9.3 A SERT (1999-2000) technology schedule/milestone roadmap for space solar power strategic research and technology investments (See section 5 for more information on the demonstration missions described in this figure.)

Certainly continued technology development is needed. Research and technology development roadmaps were prepared as part of the SERT activities (1999-2000) to determine the most important achievements needed during the next few decades. Interestingly, these developments have the potential to enable many other advances in both space and terrestrial markets. Figure 9.3 illustrates a technology development roadmap that could lead to the development of commercial space solar power satellites within a few decades. Key to this roadmap is the development and implementation of demonstrations on Earth and in space of the critical technologies. More detailed information on some of the demonstration missions developed and analyzed through the SERT systems integration process can be found in 5, Systems Integration and Demonstration Missions.

At present and continuing beyond the 2005 time frame there are many technology options to be explored at the component and laboratory test bed levels. Because there are many options in the way space solar power is collected and delivered to Earth, it is critical that an overall concept not be selected too soon and result in the lack of development of some other technology that may in the end prove to be critical to economic success.

By the 2008-2010 time frame many advances in several key technology areas will be important to make progress toward abundant and affordable power in space. Key technologies include wireless power transmission, advances solar cells, and power management systems. Examples of key demonstrations could include:

- Ground demonstrations of power relays up to 100 km to test wireless power transmission using surface towers and reflectors, and possibly reflectors suspended from airships at 20 km altitude.
- Advanced solar power technology demonstrations at the ISS to test revolutionary solar power generation and management technologies.
- Laboratory demonstrations for initial SSP platforms in the 100 kW power class.
- Lunar pole exploration using robotic rovers powered by wireless technology in the 5-20 kW power class.

These demonstrations would be consistent with technology development needs for large-scale geostationary communications satellites, solar electric power and propulsion systems for space science and near-Earth exploration applications, and continuing commercial development of low-Earth orbit, including demonstration of wireless power transmission from central power stations to other spacecraft

By the 2011-2015 time frame a mini-SPS platform could be developed to demonstrate a variety of power collection and power beaming concepts for terrestrial, in-space, and Lunar applications. Examples of key demonstrations could include:

- Development of a 1MW class pair of satellites for a SSP production platform and free flying receiver. This capability would demonstrate space-to-space wireless power transmission, and space-to-ground wireless power transmission feasibility.
- Space to space and ground to space wireless power transmission to an electric orbital transfer vehicle operating in Earth orbit.
- Lunar wireless power transmission across the surface and from orbit to robotic explorers at the poles.

These early demonstrations of wireless power transmission in space and to Earth will validate critical technologies and help resolve international concerns over space to ground use of microwave and laser energy transmission systems.

By the 2016 to 2020 time frame moderate sized SSP platforms in the 10MW power class could be developed and demonstrated. There are many applications for this size power facility including:

- Sub-scale SPS pilot plants to demonstrate wireless power transmission to terrestrial sources with connectivity to existing utility service grids
- Beamed power for new interplanetary transportation systems
- In-space power for new commercial space industries
- Full-scale in-space power plants for multiple government and commercial applications

If successfully developed, these technologies could also find broad applicability on Earth for ultra-high efficiency solar arrays, energy storage systems, and power beaming relays from power rich areas to remote power poor area.

Beyond the 2020 time frame the technologies needed for a full-scale in-space SSP prototype platform producing 1-2 GW of power or greater could demonstrate base load power transmission for terrestrial markets. This time frame is consistent with current plans for the development of very-low-cost Earth-to-orbit space transportation systems in the $100-$200/kg recurring cost range that will be needed to economically lift the vast quantity of materials required to construct this full size power facility. Ultimately, in the post-2050 time frame, very large scale, in-space SSP platforms in the greater than 10-gigawatt power class could become viable as a major and potentially primary clean electrical energy source for Earth. Such systems might also find application in providing very-large-scale power to industrial development of space resources, extensive human exploration and development beyond LEO, and in powering robotic probes to near-interstellar space during the latter part of this century.

C.10 List of Acronyms and Abbreviations

AC	Alternating current
AIAA	American Institute of Aeronautics and Astronautics
ASEB	Aeronautics and Space Engineering Board
BMDO	Ballistic Missile Defense Organization
C&DH	Command and data-handling
CDS	Concept definition study
CNES	(French) National Center for the Study of Space
CO2	Carbon dioxide
CTE	Coefficient of Thermal Expansion
DC	Direct current
DOE	Department of Energy
DOD	Department of Defense
EDF	Electricite de France
EIA	Energy Information Agency
ESA	European Space Agency
ESF	Environmental and safety factors
ESH	Environmental safety and health
ETO	Earth-to-orbit
FCC	Federal Communications Commission
FY	Fiscal year
GEO	Geostationary Earth orbit
GN&C	Guidance, navigation and control
GW	Gigawatt
HDTV	High definition television
HEDS	Human Exploration and Development of Space
HLLV	Heavy lift launch vehicle
hr	Hour
HTCI	HEDS Technology Commercialization Initiative
IAA	International Academy of Astronautics
IAF	International Astronautical Federation
IPCC	Intergovernmental Panel on Climate Change
ISAS	Institute of Space and Astronautical Science
ISC	Integrated symmetrical concentrator
ISS	International Space Station
ISU	International Space University
ITAR	International Traffic in Arms Regulations_
ITU	International Telecommunication Union
IWG	International Working Group
kg	kilogram
km	kilometer
kW	kilowatt
kWh	kilowatt-hour
LEO	Low Earth orbit
LH2	Liquid hydrogen
LSP	Lunar solar power
LOX	Liquid oxygen
m	meter
METS	Microwave Energy Transmission in Space
METI	Ministry of Economy, Trade and Industry (Japan)
MSC	Model system concept
MSFC	Marshall Space Flight Center
MW	Mega-watt
NASA	National Aeronautics and Space Administration
NEDO	National Energy Development Office (Japan)
NRC	National Research Council
OECD	Organization for Economic Cooperation and Development
OMB	Office of Management and Budget
PMAD	power management and distribution
PV	Photovoltaic
RAMS	Robotic assembly and maintenance system
R&D	Research and development
RF	Radio frequency
RLV	Reusable launch vehicle
R&T	research and technology
SEE	Societe des Electricien et des Electronicien
SEPS	Solar electric propulsion system
SERT	SSP Exploratory Research and Technology
SLI	Space launch initiative
SM&C	Structural materials and controls
SPG	Solar power generation
SPS	Solar power satellite
SSP	Space solar power
TIM	Technical interchange meeting

TMM	Thermal materials and management
UK	United Kingdom
UN	United Nations
US	United States
USA	United States of America
USEF	Institute for Unmanned Space Experiment Free Flyer
USGCRP	US Global Change Research Program
WPT	Wireless power transmission

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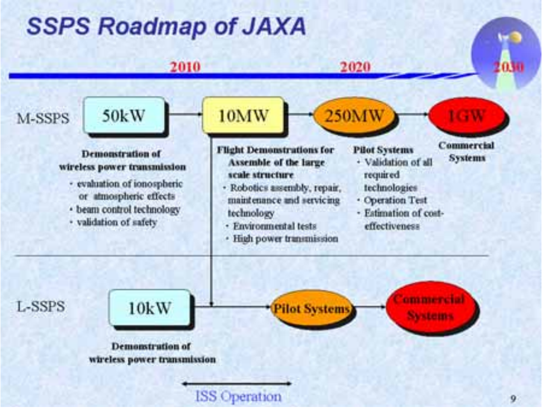
Appendix D Japanese Activities

This appendix summarizes the "Study of Space Solar Power Systems (SSPS)", Japan Aerospace Exploration Agency (JAXA) Contractor Report by Mitsubishi Research Institute Inc. This is a series of activity reports of the SSPS committee chaired by Past President of URSI, Prof. Hiroshi Matsumoto of Kyoto University. The SSPS has wider meaning than that of the SPS. Although most of these reports are written in Japanese, references are changed to similar ones written in English if available. Some of them were papers presented at international meetings.

D.1 JAXA Models



SSPS Roadmap of JAXA

2010 2020 2030

M-SSPS

50kW → 10MW → 250MW → 1GW

Demonstration of wireless power transmission
- evaluation of ionospheric or atmospheric effects
- beam control technology
- validation of safety

Flight Demonstrations for Assemble of the large scale structure
- Robotics assembly, repair, maintenance and servicing technology
- Environmental tests
- High power transmission

Pilot Systems
- Validation of all required technologies
- Operation Test
- Estimation of cost-effectiveness

Commercial Systems

L-SSPS

10kW → Pilot Systems → Commercial Systems

Demonstration of wireless power transmission

ISS Operation

9

1 1 1

The Japan Aerospace Exploration Agency (JAXA), formerly the National Administration of Space Development Agency (NASDA) in Japan studies the SPS conceptual and technical feasibility at different component levels of the SPS. JAXA proposed a 5.8GHz 1GW SPS model. Various configurations have been proposed, evaluated, and revised. The basic direction of Solar Power Satellite (SPS) development can be seen in Fig. D.1.1. It is possible to beam solar energy down to Earth using either microwave (radio) technology or laser (optical) technology. The microwave method is making especially fast progress. (Optical methods invariably have weather-related issues.)

D.1.1 Issues of 2001 Model

Fig. D.1.2 Year 2001 Reference Model[1]

In recent years, various SPS problems have been found and studied. SPS invariably has two components:

(1) Solar panel component （Power Generator）

(2) Antenna component （Transmitter）

The problem is how to put these two components together. In the 2001 study, the Sandwich Concept was proposed. In this concept, solar radiation is received on the front side, and microwave radiation is emtted from the back side. Some kind of joint module is required. When this front/back configuration is used, the release of heat becomes a formidable problem.

This model uses the Sandwich Concept. It consists of the following three parts.

Primary Mirror..............................4 x 6 km
Secondary Mirror............................2 x 4 km
Conversion Module (Sandwich Concept).........2.6 km (diameter)

These three parts are mechanically connected. The Conversion Module is always pointed at Earth, but it is necessary for the mirrors to rotate, to constantly receive solar radiation. This presents immense mechanical engineering challenges.

In any event, the Conversion Module has a severe heat dissipation problem. Excessive heat degrades the conversion efficiency of the entire module. In the JAXA model, the estimated distance between the mirror(s) and the Conversion Module is 3 to 4 km. A very large truss is required.

D.1.2 Issues of 2002 Model

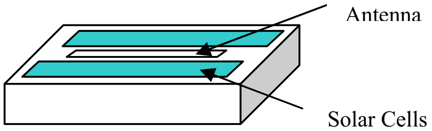


Fig. D.1.3 Transmitting antenna with solar cells.[1]

The 2002 Model was conceived to solve the main problems of the 2001 Model. Essentially, it was suggested that solar reception and microwave transmission be performed on the same surface (front side). This would free up the back side for heat release. Radiation activity (solar radiation capture and microwave emission) would occur on one side, and unwanted heat would be released on the other side. This is all illustrated in Figure D.1.3. Solar panels and microwave antennas are all on the same surface, side by side.

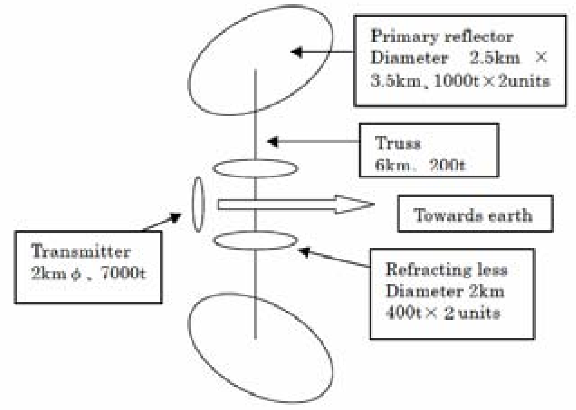


Figure D.1.4 Year 2002 Reference Mode[1]

The 2002 Model is illustrated in Figure D.1.4. The primary mirror is 2.5 km x 3.5 km. The truss is 6 km and weighs 200 tons. The conversion module is 2 km in diameter, and weighs 7000 tons. A 400 ton lens is also needed (discussed below). The lens is located between the Primary Mirror and the conversion module. All these components are mechanically connected, unfortunately.

This (2002) Conversion Module with reception and microwave transmission on the same side is feasible, but the following issues arise.

1. The implementation efficiencies of solar panels are worse than the conventional solar panel only surface. In order to obtain the same power as in the latter, the area of the solar panel must be greater.
2. To lift the system into space, some kind of modularization becomes necessary. Unfortunately, it is necessary to transmit electric current between modules when the entire SPS system is assembled in space. This interaction between modules destroys all the advantages of putting everything on the same surface.
3. A complicated refraction lens is necessary to direct sunlight from the mirror to the conversion module. This lens would be immensely difficult to design and construct.

Hence, the disadvantages outweigh the advantages of this conversion module. It is a bad idea to put all activities on the same side or same surface. Hence, it is necessary to return to the Sandwich Concept. The alternative (the 2002 Model) has too many problems. The Sandwich Concept, however, still has the "heat release" problem. This problem, as of December 2004, still has not been resolved. Some kind of technology breakthrough is needed.

D.1.3 2003 Model (Formation Flying SPS)[2]

If the SPS collects solar energy in space and sends the collected energy to the Earth, directions of a solar energy collection system (mirrors, photovoltaic arrays or others) and a power transmission system (microwave antenna or others) are different and therefore some kind of mechanical joint necessary. However, the gimbals degrade reliability.

This degradation can be avoided by using formation-flying technology. Figure D.1.5 illustrates a conceptual image of the formation-flying SPS proposed by JAXA. The SPS consists of two primary mirrors and the SPS main module (secondary mirrors, power converters and power transmitters). The SPS main body will be placed on the geostationary Earth orbit (GEO), and the two primary mirrors will be placed a few kilometers north and south of the main body.

The solar collection mirrors receive the solar pressure from the Sun. Since the primary mirrors are tilted against the GEO plane, this solar pressure is divided into the horizontal (parallel to GEO plane) force and the vertical force. The horizontal force should be canceled using some kind of actuators such as the ion thrusters. The remaining vertical force acts as the lifting force that moves the mirrors away from the GEO plane. The mirror also receives the gravitational force caused by the mirror's orbital motion. If the gravitational force is cancelled by the lifting force generated by the solar pressure, then the primary mirrors can stay north and south of the SPS main body, while the primary mirrors are placed on a slightly inclined orbit against the GEO.

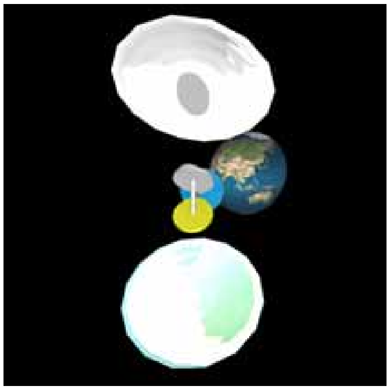


Figure D.1.5 Year 2003 Reference Model[1]

A SPS concept which utilizes formation flying technology is introduced. The solar pressure can lift the large light weight solar collection mirror away from the GEO plane. This technique allows three satellites to be placed on three parallel orbits. Such orbits can be exist around the GEO if the satellite is large and light enough to be lifted by the solar pressure. It is a matter of future studies to determine how to control the shape and attitude of such light and huge structures.

D.2 Launch and Transportation

D.2.1 Launch

Two vehicles are to be developed for the launch and construction of SPS. One is a Reusable Launch Vehicle (RLV) to transport heavy materials, at reasonably low cost, to a Low Earth Orbit (LEO) where assembly work will be conducted. The other is a low-thrust Orbital Transport Vehicle (OTV) to lift the SPS from the LEO to the final orbit (geosynchronous Earth orbit; GEO). These two rocket technologies are essential for realizing the SPS system. The transportation cost occupies a fair percentage of construction cost of the SPS, and most of the transportation cost is occupied by that of RLV's.

D.2.2 Transportation[3]

Space Solar Power Systems (SPS), which are assembled in a low-Earth orbit (LEO) and transported to a geostationary Earth orbit (GEO) by solar electric propulsion orbital transfer vehicles (EOTV), are severely affected by both radiation belts and space debris (see [4],[5]). If the solar cells of the SPS are already significantly degraded by radiation when it arrives in GEO, it will be necessary to launch more payloads to compensate for the degradation in order to secure the predetermined amount of power generation. This will increase the required amount of transportation by the reusable launch vehicle (RLV). A 1GW SPS has dimensions of kilometers, and its cross-sectional area is as large as 100 times that of the international space station (ISS). Therefore, we are anxious about debris impacts during assembly in LEO. This subsection introduces the optimum method of in-orbit transportation that minimizes the RLV transport requirement, considering both cell degradation and debris impacts. Although degradation by radiation can be minimized by using CIGS cells, both indium and gallium resources are in short supply. In particular, supplies of indium are predicted to be exhausted in less than 20 years. Using thin-film cells of abundant silicon has therefore been proposed (see [6]).

The following two scenarios are examined. (scenario 1) The orbit where the SPS is assembled is not limited to LEO, but higher orbits are also studied. A high-thrust OTV (HOTV) with a LOX/LH2 (liquid oxygen/liquid hydrogen) engine is used for transportation to the higher orbit. In scenario 1, thin-film cells are supposed to already be attached to the frames at launch. (scenario 2) The case where only thin-film cells are transported to GEO in a short period of time using the HOTV in order to avoid SPS cell degradation is examined.

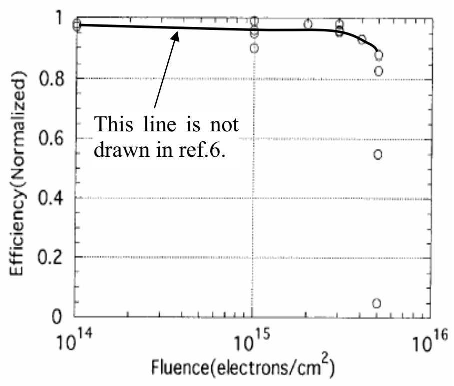
The results are as follows, where m_{req} is defined as the mass of the SPS on GEO that produces 1GW on the ground with no cell degradation and currently estimated to be about 10 thousand tons.

(1) The RLV transport amount increases rapidly when the departure altitude decreases and the remaining factor after 10 years on GEO is 0.925. This was caused by the necessity of a larger EOTV to shorten the period of the forward trip and to keep the remaining factor after one round trip larger than 0.6.

(2) If the remaining factor after 10 years on GEO is 0.925, the minimum RLV transport amount for the basic HOTV is $2.50m_{req}$ (at 7000km), and the minimum RLV transport amount for the advanced HOTV is $2.34m_{req}$ (at 8000km). The improvements from scenario 1 are not enough.

(3) If the remaining factor after 10 years on GEO is improved, the increased RLV transport amount at lower start orbits can be reduced. The RLV transport amount from lower orbits becomes flat when the remaining factor after 10 years on GEO is between 0.93 and 0.94. We call this the "Critical Remaining Factor (CRF)" because the effect of the high specific impulse of the EOTV balances the influence of the cell degradation. If a remaining factor exceeding the critical remaining factor is realized, the EOTV start from 500km altitude is optimum.

(4) If the degradation characteristics of the thin-film Si cells cannot be improved, a propulsion system with a specific impulse exceeding that of the LOX/LH2 engine is required for the HOTV. Solar thermal propulsion and laser propulsion are candidates. The minimum RLV transport amount for the SOTV (LOTV) is $2.04m_{req}$ at 8000km ($1.68m_{req}$ at 9000km).



This line is not drawn in ref.6.

Fig. D.2.1 Degradation of a-Si cell by 1.0MeV electron irradiation test (from [7])

(5) Figure D.2.1 presents the result of the 1MeV-electron irradiation test of a-Si cells (see [7]). The result indicates significant degradation at a fluence[8] of $5\times10^{15}/cm^2$. Since the fluence accumulated for 30 years on GEO is about $1.5\times10^{15}/cm^2$, this a-Si cell would be acceptable. When the remaining factor of the EOTV cells decreases to 0.6 after one round trip, however, the accumulated fluence reaches about $10^{17}/cm^2$. If the a-Si cells degrade in space as shown in Fig. D.2.1, the EOTV cannot return. According to [7], the a-Si cell was found to have an annealing effect. Since a-Si cells in space are exposed to a significantly lower rate of radiation than in the irradiation test, the real degradation might be less than indicated in Fig. 6 due to the annealing effect (see [7]). We should determine the upper limit of fluence for a-Si cells by a demonstration flight on a small spacecraft.

(6) Previously in scenario 2, we assumed that the SPS is assembled in GEO. Here, we examine the possibility of assembly at the departure orbit of the EOTV. When the remaining factor after 10 years on GEO is larger than the CRF, the departure altitude of the EOTV becomes 500km. Assembly at that altitude, however, is undesirable due to debris impacts. When the remaining factor after 10 years on GEO exceeds the CRF, the departure altitude of the EOTV becomes 7000km to 9000km. Although assembly at these altitudes is not influenced by the debris impacts, this region is not good for spacecraft assembly due to the radiation environment. Therefore, assembly at GEO is preferable.

Efficient transportation between low-Earth orbit and geostationary Earth orbit is an important problem for realizing Space Solar Power Systems (SPS). During the in-orbit assembly phase and the in-orbit transportation phase, the SPS is exposed to severe environments of both space debris and radiation. Radiation will significantly degrade the SPS solar cells.

The Reusable Launch Vehicle (RLV) transport cost for the SPS is currently estimated to be about 1/4 of the total cost, assuming an RLV transport amount of $1.3m_{req}$. Therefore, reducing the RLV transport amount to near $1.3m_{req}$[9] is important. In scenario 1, we investigated assembling the SPS at an altitude below GEO then transporting it to GEO by EOTV. The thin-film Si-cells are transported by the EOTV attached to the supporting frames in scenario 1. It is found that the assembly altitude should exceed 3000km in order to reduce the frequency of the debris impacts to a safe level and that the SPS should not be assembled at any altitude between 3000km and 11,000km in order to avoid degradation of the cells. Therefore, the assembly altitude was limited to above 11,000km in scenario 1. This made it difficult to reduce the RLV transport amount to below $3m_{req}$.

Next, we investigated scenario 2 in which the thin-film Si-cells only are transported directly to GEO by the HOTV. When the cell's remaining factor after 10 years on GEO is 0.925, the RLV transport amount with transport between the RLV orbit and the EOTV departure orbit by the LOX/LH2 engine was decreased to about $2.4m_{req}$, but this was not sufficient. The study with various values for the remaining factor after 10 years on GEO revealed that if a remaining factor larger than the CRF is realized, the EOTV departure altitude of 500km becomes optimum and the RLV transport amount decreases to under $2m_{req}$. If the degradation characteristics of the thin-film Si-cells cannot be improved, propulsion systems with specific impulses larger than that of the LOX/LH2 engine are required. It is also found that the RLV transport amount can be less than $2m_{req}$ if solar thermal or laser propulsion is employed in the HOTV.

This investigation found that both improving the degradation characteristics of the thin-film Si-cells and the research/development of new propulsion systems such as solar thermal and laser propulsion are important for realizing the SPS.

D.3 Solar Power Generation

D.3.1 Solar Concentrator

D.3.1.1 Important Technical Issues

The SSPS operates at a geostationary position and converts solar energy into radio waves or laser light, providing a stable source of electric power to Earth.

1. Solar light acquisition
2. Supplying energy

Operating in space is difficult. Here are three harsh properties of the space environment.

Table D.3.1 Longevity of Polymer Molecule Film

Topic	Degradation Factors
Damage in space	space radiation, lack of air
	Debris, gases
Chemical degradation	thermal damage of polymer molecules
	heterogeneous structure and impurities
	sunlight damage
Physical and mechanical degradation	metal fatigue, and the like
	durability to chemicals (chemicals that might be needed for thrusters)

1. No gravity
2. Strong radiation
3. Near vacuum

Solar cells absorb sunlight and convert it into electricity, but the process is not fully efficient. Anything not converted into electricity is converted into heat or light. It depends on the device, but some wave bands are not accepted by the device. These wave bands may be ultraviolet or infra-red. In any event, it is possible for these frequencies to damage the device if the dosage is high. High-energy UV may degrade devices or damage them. Furthermore, infra-red may warm up devices, degrading their efficiency. Therefore, it is prudent to devise means of blocking unwanted wave bands to improve the longevity and performance of solar cells. Only desirable frequencies should be allowed to reach the solar cells. Therefore, one main topic of light collection is wavelength control technology. To do this well, we need to understand device characteristics more thoroughly, as well as to understand how reliable devices must be in the space environment. We mention the following with respect to wavelength control.

We presume that maximum power output occurs when light strikes the solar panel perpendicularly. Accordingly, incident light must be kept perpendicular to maintain maximum power output. Solar power generation on Earth can be done with and without tracking. It has been reported that power output can be doubled with tracking. In space, the primary optics can capture solar radiation, and the secondary optics can provide solar radiation in a steady fashion to the solar cells. Sunlight tracking is a significant issue in itself and requires a high degree of sophisticated technology.

In recent years, new ideas have taken root. New solar cells with high light collectivity have been demonstrated. For example, Sun Power Company (in the USA) has developed a solar cell grown from a single silicon crystal that has an efficiency rate of 25% when injected with solar radiation 200 to 300 times the natural amount. This is a "tandem" device. However, recent research has shown that a conversion efficiency of 35% is achievable when sunlight is concentrated by a factor of 1000. This type of light concentration technology can be used for both microwave-based and laser-based SPS systems. Current thinking about laser systems is that sunlight would directly excite a laser. However, it is widely assumed that some light concentration (factor 1000) is needed for a laser system as well. Moreover, it is also necessary to block unwanted wavelengths. Hence, microwave systems and laser systems have some overlap in research.

If the secondary optics is used for light concentration or solar-pumping lasers, a leak of light leads to a large loss. It would be effective to use a concentrator like CPC (compound parabolic concentrator) that can concentrate the light without tracking in combination in order to decrease the loss in the secondary optics. For solar cells, homogeneity of sunlight is important. It would be necessary to discuss how to homogenize the concentrated light in space.

D.3.1.2 Wavelength Control

"Wavelength control" means allowing only certain wavelength bands to strike the solar cell surface. Other bands may degrade the life and performance of the solar cell. A wavelength-control device is inserted between the light-collecting system and the energy converter (solar cells). There is a variety of wavelength control devices to select from, and they are mainly optical filters. Existing choices are:

#1 absorption type filter,
#2 dielectric multi-layer filter, and
#3 diffraction grating filter.

Based on our findings, Filter #2 is durable enough for SPS application, but the other two filters are not durable enough for applications where sunlight is concentrated. If light concentration is not used, then the filter can be applied (coated onto) the primary mirror. It might be possible to coat the solar cell as well.

Hereafter, more study will be needed on multi-layer membrane coatings for use in space for primary optics. More work will be needed on dielectric multi-layer filters ("hot mirror") to be used in the vacuum of space. The durability of these mirrors must be confirmed.

On the light concentrators for the SPS, it would be prudent for the concentration mirrors to separate the spectral components of the solar radiation into the component that contributes to the energy conversion and other components, and allow only the former to reach the solar cells.

While glass is easy to work with and is durable in space, it has drawbacks if it is to be used for mirrors. Glass is heavy. Presently, it is felt that the best way is to use large-molecular film coated with a dielectric multi-layer. In this approach, much care must be taken with the longevity of the system. Refer to Table D.3.1 to see the topics for "Longevity of Large-Molecule Film."

Kapton (developed by Dupont in 1964) is a good example of a material developed for the harsh space environment. Kevlar was also developed for space missions. More chemical engineering research is needed for more and better materials for use in space.

For the following reasons, degradation of the light collectors cannot be tolerated. The expected lifetime of the SSPS must be long enough to cover its "energy payback time." To do this, the solar array must last at least 20 years. (End-of-life is defined as when power output drops to half of the initial output.) The solar cell itself is a severe restraint on the lifetime of the entire SSPS. Therefore, no allowance can be made for the mirrors or other light collectors. It is vital for the success of the SSPS that we determine the durability of mirrors and other light collectors for use in space. It is an important parameter that we yet do not know enough about.

D.3.1.3 Summary

Solar energy capture technology (light-collection technology) is a vital technology for securing sufficient energy. This technology can be exploited by SSPS, which involves putting a large solar-concentration system in geosynchronous orbit around the Earth. Solar power received near the Earth (the region between the top of the atmosphere and geosynchronous orbit) is 1.4kW per square meter. This light must be captured by conversion devices while minimizing reflection and other forms of loss.

For example, in photoelectric conversion, secondary light-collection issues can be resolved, the need for homogenizing can be determined, the need for wavelength filtering can be established, and so on depending on whether light concentration is employed. In short, optical design considerations are very important to the overall system. At the same time, it is imperative that the SPS be built as a super-light structure, as it must be installed in a geosynchronous orbit in space. Material for the solar light collection devices and systems must also be extremely light. Because the space environment is severe (vacuum, space radiation, weightlessness, debris, etc.), conservative design is needed for devices and systems to ensure long-life performance in space. Securing the long-life performance of devices and systems (and their maintenance) should be discussed by all parties concerned.

D.3.2 Power-Generation Technology

D.3.2.1 Concept of Power-Generation System

To realize a commercial SPS, there are a few outstanding issues that must be tackled for solar cells. These are

1. vast weight reduction,
2. vast cost reduction, and
3. mass production feasibility/

We cannot expect high-efficiency performance from thin-film solar cells, but we can expect good performance in terms of weight and conservation of natural resources. Another option is to use rare-earth elements for solar cells (III-V class elements). There are advantages and disadvantage here as well. The main advantage is that they can have much higher efficiency, and when combined with light-concentration techniques, far fewer solar cells are needed. However it is not clear how easily rare-earth solar cells can be mass produced. The current SPS concept seeks to fabricate the solar cell portion and microwave transmitter portion together as one frame. Hence, it is desirable that the surface area of each is nearly the same. Once the required power is established, then system parameters can be figured out, the area of SPS microwave transmitting antenna, the area of the rectenna, and the area of the solar panel. Assumptions must be made about things such as radiated energy density, and solar cell conversion efficiency.

The area of the SPS microwave transmitting antenna depends upon the area of the Earth-based rectenna and the microwave energy density. In contrast, the area of the solar panel depends upon the solar radiation energy density (basically fixed), solar cell conversion efficiency (might improve with better technology), and necessary power (the amount of power that must be generated by the entire system).

The conversion efficiency is defined by the solar cell type (technology), and the necessary power depends upon the system design. It is possible to decrease the area of the solar panel array by using light concentration techniques; however there are limits to this approach because the solar panel will overheat.

In the year 2001, the world had 391MW of solar cell capacity. Of this, 160MW exists in Japan. Of this, 160MW was in Japan. In today's world, over 80 percent of capacity is furnished with single crystal and polycrystal silicon solar cells. Japan is seeking to raise its capacity to 4820MW by the year 2010. To achieve this, considerable cost reduction is necessary. The necessary R&D is underway at research centers around the world. Accordingly, we expect that by 2010, CIGS (copper indium gallium di-selenide) and a-Si thin-film solar cells will become the main stream. Information regarding mass production, deployment accumulation, and cost of solar cells is presented in Figs. D.3.2.1 to D.3.2.3

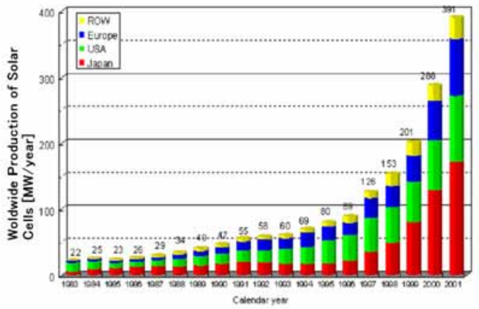
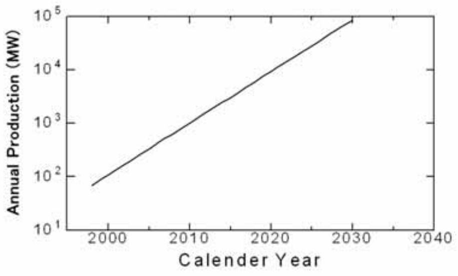


Fig. D.3.2.1 Trajectory of Solar Cell Production[10]
(NEDO Sun-Wind Technology Development Center)



3 2 2 (From
NEDO Website)

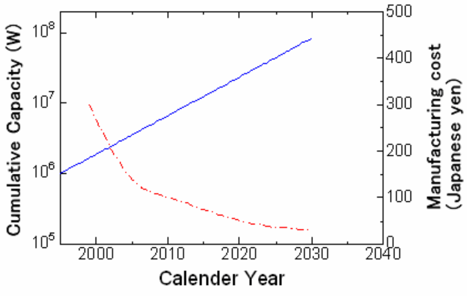


Fig. D.3.2.3 Rising solar cell application and declining manufacturing cost (From NEDO Website)

Two types of power generation systems were studied to resolve the problem of current generation solar cells and the problem of heat in satellites. Fig. D.3.2.4 presents
(a) the massive light-concentration approach and
(b) the super light-weight thin-film approach.

The necessary surface area for each system for a 1GW system is shown in Table D.3.2.2. For the light-concentration approach, high-efficiency III-V class material is presumed. For thin-film, some combination of CIS and amorphous silicon is assumed. Light-concentration can be low-rate (concentration of a few hundred) or high-rate (concentration of a few thousand). In any event, light must shine on solar cells uniformly. Heat that builds up in the solar cells must be conducted to heat radiators and radiated into space. With the super light-weight thin-film approach, the surface area of the solar array is necessarily large, 3.5 to 4.2km square, because, although light in weight, thin-film cells have low conversion efficiency. If the microwave antenna is about 2 km in diameter, then the solar side becomes larger than the transmitter side. In this case, elaborate power distribution is necessary within the SPS. Perhaps it is more promising to use CIS/amorphous silicon technology solar cells. These promise to be more rugged in the space environment. If the cover glass can be reduced in weight, then substantial overall weight reduction can be achieved for the SPS.

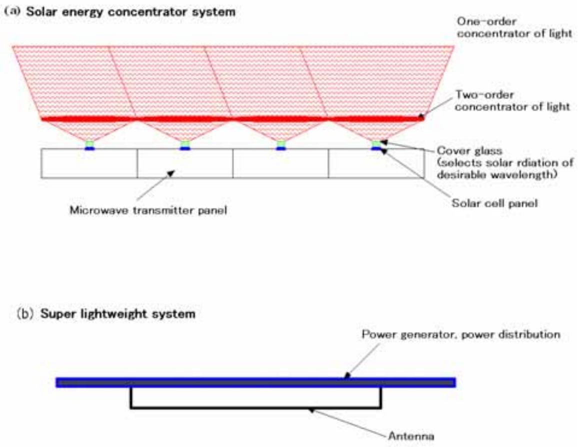


Fig. D.3.2.4 Power generation concept[11]
(a) Solar energy concentrator system
(b) Super lightweight thin-film system

Table D.3.2.2 Cell Area of 1GW System[11]

Losses due to the atmosphere	0.98
Effect of summer	0.97
Seasonal variation	0.91
Connection efficiency (to commercial power grid)	0.95
RF-DC Conversion efficiency	0.76
DC-RF Conversion efficiency	0.75
Collecting power efficiency	0.93
Total (excluding solar cell)	0.44

Solar Cell	III-V	CIS	a-Si
Sunlight-DC conversion efficiency	0.40	0.15	0.10
Radiation damage (after 30 years)	0.80	0.95	0.95
Total	0.32	0.14	0.10

Entire system	0.14	0.06	0.04

Solar radiation strength	1353.00	W/m^2

Power Generation	Power Generation (GW)	2.30

Collected light	1000.00	1.00	1.00
Solar cell area	m2	km^2	km^2
1GW	5309.32	11.92	17.88

D.4 Thermal Control Technology

D.4.1 Thermal Control of Microwave SPS

D.4.1.1 Flow of energy inside the SPS

Energy flow and internal heat of the Conversion Module shall be discussed here to study thermal control. The main components of the Conversion Module are the generator (array of solar cells) that converts sunlight into DC and the transmitter (magnetron) that converts DC into microwave radiation. Sunlight is directed to the generator, either by reflection (using mirrors) or by refraction (using Fresnel lens), or a combination of both. Sunlight striking the solar panel is partly reflected and partly absorbed. The absorbed energy is converted into heat energy and electric energy. The electric energy is wanted; the heat energy is unwanted but unavoidable. The electric energy is converted to microwave radiation by the transmitter for transfer to Earth. This, too, produces unwanted heat. Hence, unwanted heat comes from the solar cells and the transmitter. Managing this unwanted heat is the subject of Thermal Control.

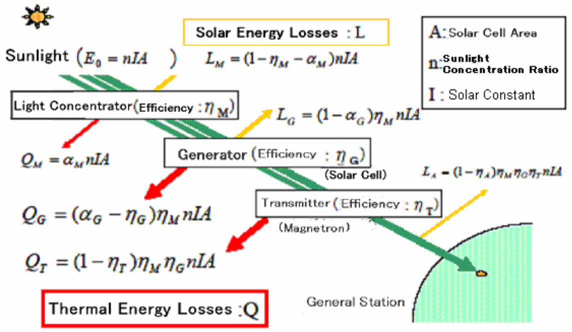


Fig. D.4.1 Microwave Transmission Energy Flow[11]

D.4.2. Study of Thermal Situation

D.4.2.1 Orbital Situation of Reference Model

The following was done in this study.

(1) A simple model was created to explore the surplus heat of the Conversion Module of the Year 2001 Reference Model.

(2) A simple model was created to explore the surplus heat of the Conversion Module of the Year 2002 Reference Model.

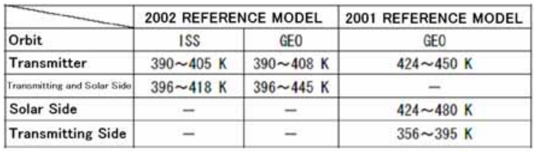
(3) Day/night temperature changes of ISS and GEO positions were compared.

See Fig. D.4.2 (D.4.3) for the 2002 (2001) Reference Models.

The GEO calculation results for temperature hange of the 2002 Reference Model are shown in Fig. D.4.4. The horizontal axis is time of day. At 2400, the temperatures of the transmitter and solar panel decrease due to eclipse. At 0600 and at 1800, the temperature dips because sun rays and the solar panel are nearly parallel.

The calculated GEO temperature changes for the 2001 Reference Model are shown in Fig. D.4.5. Except for the power transmission module, the temperatures of the 2001 model are 40 K higher. Hence, from a thermal perspective it is safe to say that the 2002 model is superior to the 2001 model. Even when thermal control devices are utilized, the overall weight is reduced because less heat needs to be dissipated. Fig. D.4.6 plots the calculated temperature changes of the 2002 model when the SPS is in low orbit (ISS orbit). Compared to Fig. D.4.4 (GEO), the range of the temperature change is smaller. This can be explained by the short orbit period of the ISS. Table D.4.1 presents the range of temperature change of each model. Operational devices become hot for all situations and models. It is apparent that some means of thermal control, for example attaching a radiator or radiators, is needed.

Table D.4.1 Comparison of Thermal Aspects of Reference Models[1]



	2002 REFERENCE MODEL		2001 REFERENCE MODEL
Orbit	ISS	GEO	GEO
Transmitter	390～405 K	390～408 K	424～450 K
Transmitting and Solar Side	396～418 K	396～445 K	—
Solar Side	—	—	424～480 K
Transmitting Side	—	—	356～395 K

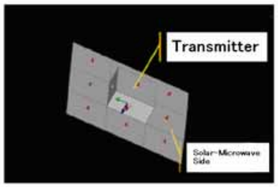


Fig. D.4.2 Single Module of 2002 Reference Module[1]

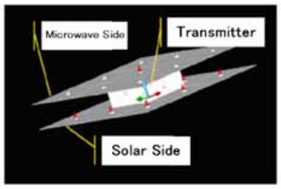


Fig. D.4.3 Single Module of 2001 Reference Module (sandwich design)[1]

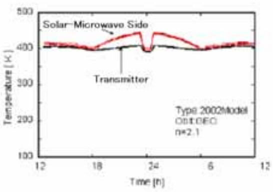


Fig. D.4.4 2002 Reference Model Temperature Changes at the Equator[1]

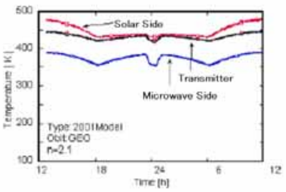


Fig. D.4.5 2001 Reference Model Temperature Changes at the Equator[1]

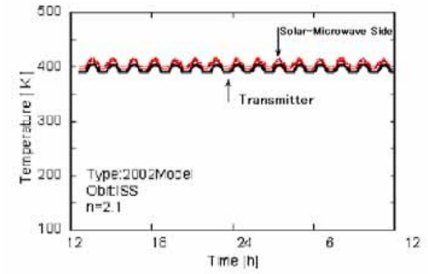


Figure D.4.6 2002 Reference Model Temperature Changes at ISS Orbit[1]

D.4.3. Temperature of power transmission module

D.4.3.1 Temperature of the Generator (Solar Panel)

First, we calculated the surface temperature when sunlight hits the surface of the solar panel directly. The results of the calculation are presented in Fig. D.4.7. Horizontal axis is injected power (kilowatts per square meter). The vertical axis is temperature in centigrade. Hence, if solar radiation is concentrated by a factor of 4, then the surface temperature soars beyond 100 deg C, leading to complications. Under these temperature conditions, electric generation efficiency drops and the structural temperature (cell temperature) exceeds the goal of less than 100 deg C. Operating above this requires system design for that situation. Backside thermal radiation contributes very little to thermal stabilization of the entire system. Accordingly, from a purely thermal perspective, concentration of sunlight (operating above factor 1) is feasible.

Calculation results are plotted in Fig. D.4.8 and indicate that the internal temperature of the solar cells soars to 200 deg C in the worst case. Therefore, if sunlight is distributed over the solar panel in a Gaussian manner, then a complicated thermal control scheme is needed to deal with high internal temperatures that are possible under real operating conditions.

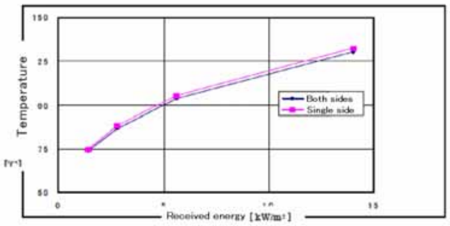


Figure D.4.7 Temperature of Basic Solar Cell Module as affected by light concentration rate[12]

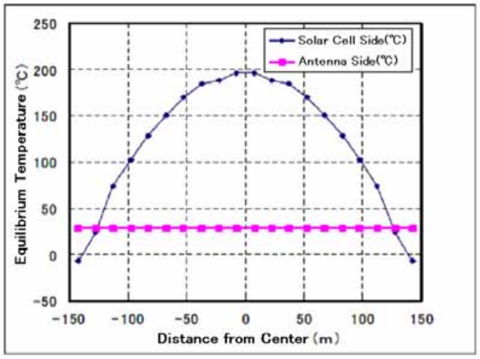


Fig. D.4.8 Equilibrium Heat Distribution of Solar Cell Side[12]

D.4.4 Reducing Thermal Burden on Solar Cells

D.4.4.1 Blocking Infra-red Radiation

One method of thermal control is to block infra-red radiation from the Sun, either reflecting it, or using filters that block it. Results are shown in Table D.4.2.

0.78μm wavelength radiation is absorbed by 47%. Also, crystalline silicon cell saturates at 1.24μm, and so we hope to reduce the absorption rate to 18%. However, electricity generated over all wavelengths of amorphous silicon cells is lowest; that of microcrystal silicon cells and that of crystalline silicon cells are about 1.2 and 1.5 times of that of amorphous cells.

There are two promising approaches. First, crystalline silicon cells can be utilized to reduce unwanted heat by 20 percent. Second, amorphous silicon can be tried to reduce unwanted heat by 50%.

Table D.4.2 Energy absorption saturation rate and Black Body energy saturation rate (at cut-off wavelength of 0.78μm)

Wavelength (μm)	a-Si:H	μc-Si:H	c-Si	Black Body
0.7750	0.9960	0.9018	0.8280	0.5275

D.4.4.2 Wavelength Selection

The concept of wavelength selection is shown in Fig. D.4.9. Essentially, unwanted radiation is reflected, so that it does not reach the solar cells. Thus, solar cells can operate more coolly and more efficiently.

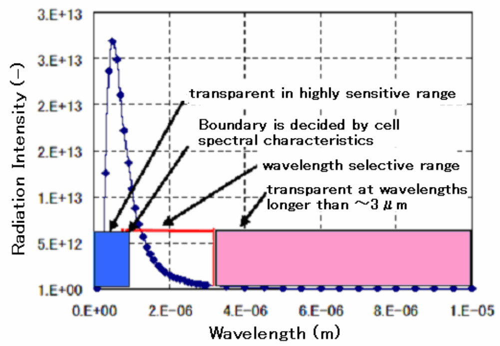


Fig. D.4.9 Effects of a spectral filter set between the Sun and the solar cell[11]

We considered the situation when spectral selection is used for the solar cell. In Fig. D.4.10, three types of selectors are considered. Type 1 means a-Si:H; Type 2, CdTe; and Type 3, CIS type. In this study, we consider methods that have quantum efficiency better than 0.5 for the solar generator. The generation efficiency of each cell is assumed to be 15% (sunlight) and constant in the effective range.

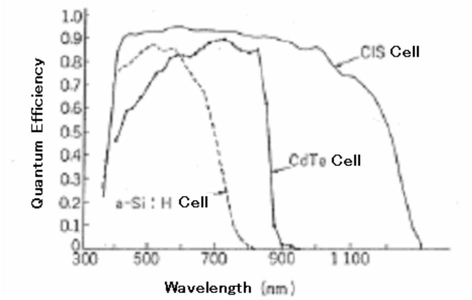


Fig. D.4.10 Spectral sensitivities of solar cells[13]

The sunlight concentration rate for each type is considered in Fig. D.4.11. Each type is able to release some unwanted heat away from the solar panels. Type 1 appears to be especially effective. Compared with no spectral selection, Type 1 reduces heat to 32%. Type3 reduces heat to 60 percent, although its effectiveness is low. When sunlight concentration does not employ a film, excess heat is about one kW/m^2. With Type 1, it is about 0.32kW/m^2. With Type 3, however, it is about 0.60kW/m^2.

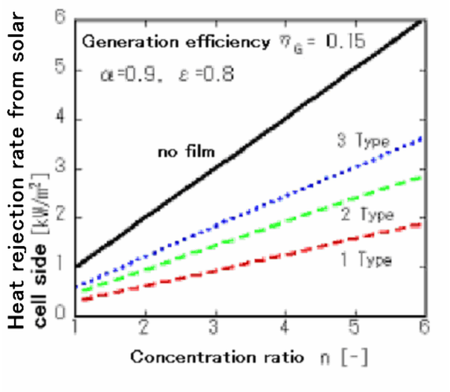


Fig. D.4.11 Relation between sunlight concentration ratio and heat rejection rate (with spectral filter attached)[11]

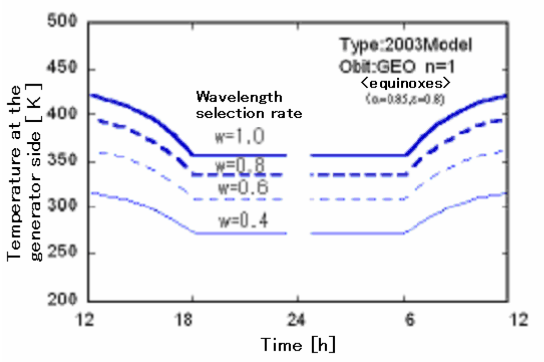


Fig. D.4.12 Calculation results[11]

It was found that for Type 1 can dissipate the heat of six-fold concentration when wavelength selection is employed. Without wavelength selection, the heat of just two-fold concentration can be dissipated.

Simplified calculations were performed for on orbit conditions. Results are plotted in Fig. D.4.12. When the sunlight concentration factor is one and unwanted wavelengths are suppressed by 60 percent, then this has the potential to keep the temperature below 100 ºC. Accordingly, for Type 1 and Type 2, it is possible to keep the temperature below 100 ºC even without thermal control.

D.5 Microwave Power Transmission on SPS

D.5.1 SPS Considerations

(1) SPS system Parameters

Table D.5.1 presents the power density characteristics of one antenna element for the following two situations.

1) Geostationary position (36,000 km from earth);
frequency of 5.8 GHz; power in the 1 GW range.

2) NASA reference system; 2.45 GHz; power in the 5 GW range.

In the NASA reference system, each antenna element must handle a maximum of 185W of microwave power. However, in the 5.8GHz system, power to be handled ranges from 1 to 6 W.

(2) Weight Calculations for SPS Transmitters

Please see Table D.5.2 for a comparison of electron tube technology and semiconductor technology (1 GW system at 5.8GHz). Calculations were performed for antenna sizes of 1 km and 2.6 km (diameter). With electron tube technology, if the transmitter weight can be reduced to 1/10, then a 1-km antenna would weigh around 8400t. With semiconductor technology, if the transmitter weight can be cut down to 1/10, then a 1-km antenna would weigh 13,000t. If the antenna and phase shifting hardware can be reduced to 1/2, then a 2.6-km SPS would weigh 25,000t. To summarize: To realize an SPS, considerable weight reduction is needed in the hardware (antenna, microwave amplifiers, etc.). This hardware must be reduced to one tenth of current levels. For semiconductor technology, much more circuit integration is needed.

Table D.5.1 Power output per single antenna element[16]

Frequency	5.8 GHz		5.8 GHz		2.45 GHz	
Diameter of transmitting antenna	2.6 kmϕ		1 kmϕ		1 kmϕ	
Amplitude taper excitation	10 dB Gaussian		10 dB Gaussian		10 dB Gaussian	
Output power (beamed to earth)	1.3 GW		1.3 GW		6.72 GW	
Maximum power density	63 mW/ cm^2		420 mW/cm^2		2.2 W/ cm^2	
Minimum power density	6.3 mW/ cm^2		42 mW/ cm^2		0.22 W/ cm^2	
Antenna spacing	0.75 λ		0.75 λ		0.75 λ	
Per antenna element	Max 0.95 W (3.54 billion elements)		Max 6.1W (540 million elements)		Max 185 W (97 million elements)	
Element	800 W magnetron	solid-state amplifier	800 W magnetron	solid-state amplifier	800W magnetron	solid-state amplifier
Maximum power part	840 divisions	1 W **	130 divisions	6 W **	4 divisions	200 W*
Minimum power part	8400 divisions	0.1 W**	1300 divisions	0.6W**	43 divisions	20 W

Power combining amplifier. **Single amplifier.

Table D.5.2 SPS Weight Considerations[16]

	Transmitter based on tubes	Transmitter based on semiconductors
Main unit	20～50 g/W	50～60 g/W
SPS 1.3GW output power	26kt ～65kt	65kt～78kt
Power distribution, phase shifter weight	About the same weight as the transmitter	About the same weight as the antenna
1km antenna (3kg/m^2)	About 2,400 t	
2.6km antenna (3kg/m^2)	About 16,000t	
FRAME	10% of total SPS (1992 Japan Model)	
1km, 1.3GW Transmitter part of SPS	Over 60kt	Over 76kt
2.6km, 1.3GW Transmitter part of SPS	Over 75kt	Over 106kt

Note: “kt” = kiloton

D.5.2 Microwave generators

D.5.2.1 Power generation devices and circuits

Many advanced solid-state devices have recently been developed or improved. For instance, wide-bandgap devices such as GaN have significant power outputs particularly at relatively low microwave frequencies of 2.4 and 5.8 GHz ranges. Linearity and efficiency are always desired, not only for these devices but also many others. However, III-V based devices have disadvantages over Si-based devices, from the view point of huge quantities required for SPS, simply because III-V materials are limited and more costly. Associated circuit technologies such as high-efficiency amplifiers need to be advanced while maintaining the linearity. This is a challenge even for conventional communication and radar applications but is particularly relevant to SPS where the total power is huge and loss abatement in space is a problem. Power-combining schemes have also been investigated. To date, however, no convincing results practical to MPT have been realized.

It is important to seek alternative solutions such as vacuum tube technology while keeping the efficiency, linearity and reliability issues in mind.

D.5.2.2 Comparison of microwave transmitting devices

(a) Microwave Vacuum Tubes

For the SPS, the technology employed for generating microwave radiation is an extremely important subject. The transmission of microwave energy often uses 2.45 GHz and 5.8 GHz of the Industry, Science, and Medical (ISM) band. Broadly speaking, there are five types of microwave generation methods to consider.

(1) magnetron
(2) klystron
(3) TWT
(4) FET semiconductor
(5) hybrids of the above technologies

As can be seen from Table D.5.3, state-of-the-art devices can convert DC to RF at high rates of efficiency.

●Phase-Controlled Magnetron

The magnetron is widely used in microwave oven and is a relatively inexpensive oscillator to manufacture. It can be driven by stabilized direct current (DC). Frequency control has been improved,[14] and phase control is also possible.[15] At Kyoto University, a phase-controlled magnetron is being developed. This magnetron module consists of:

(1) high voltage power supply,
(2) waveguide circulator,
(3) waveguide directional coupler,
(4) single board computer, and
(5) chassis.

With this module, power can be generated at 45g/W. The demerit of the phase-controlled magnetron is that it lacks a track record in space. In addition, a cooling system may be required when used in space. Magnetrons manufactured for microwave ovens are dominated by two nations: Japan has 45% of the world market, and South Korea has 55% of the world market. This means the rest of the world has little experience with making magnetrons on a large scale. With 45.5 million units built, and each magnetron capable of 1kW on average, there is a net global capacity of 45.5GW (this is the track record for microwave ovens). This is sufficient manufacturing experience for producing magnetrons on a large scale for SPS.

Table D.5.3 Characteristics of electron tubes[16]

Tubes	Phase-controlled magnetron	TWT amplifier	Klystron amplifier	Microwave Power Module (MPM)
Efficiency	Main unit 75% level Phase-control 60% level	Beam recovery type 60〜67%	Main Unit max 76%	50％
Output	several 10^2 ~ 10^3 W	several 10^2 W	10^2 ~ several 10^7 W	180W
Weight (including power supply)	45g/W level (2.45GHz) 20~30g/W(5.8GHz)	20g/W	40〜100g/W	6.4g/W
Harmonics	Second: -55dBc，Third: -80dBc，Fourth: -70dBc, Fifth: -75dBc，Sixth: -70dBc (actual measurement)	less than -70dBc	less than -70dBc	
Notes	Current control feedback	Proven record in space		C Band

● Traveling Wave Tube （TWT）

This high-gain microwave amplifier is widely used in television broadcasting satellites and communication satellites. The TWT has a proven track record in space. The disadvantage of using it for the SPS is that it had a low DC-RF conversion efficiency. In 1980, it was not a serious candidate for SPS use. However, in recent years, research has taken place so that systems can make use of "lost" energy. In this way, the net conversion rate has risen from 60 to 67 percent.[17,18] The TWT has the following track record in space: 150W at 2.45GHz at 3kg (the TWT weighs 1kg, the power supply weighs 2kg). Hence, it can deliver 20g/W.

● Klystron

The klystron is capable of delivering very high power (tens of kilowatts to a few megawatts). However, it requires a ponderous power supply (it requires a heavy magnet).

At 2.45GHz, a commercially available klystron can deliver 80kW of power, but is very heavy. The device weighs 100 kg, the power supply weighs 8000 kg, and the weight of the magnet must be added. It generates 100g/W. In C band, a commercially available klystron can deliver 3.2kW but requires a 34kg device (permanent magnet) and a 135 kg power supply. It can achieve 40g/W. From the weight/power perspective, the klystron is by no means inferior to magnetron and semiconductor devices. It can be surmised that the klystron was selected for the 1980 SSP Reference Model, because of its high conversion efficiency (76% if the device alone is considered), low harmonic emissions, and modest weight. The klystron is often used for uplinks (earth stations beaming to orbital satellites).

Because production data on TWTs and klystrons is not publicly available, broad conclusions cannot be extracted. From the point of international competitiveness, Japan cannot be dismissed as a player in this field because device production is occurring in Japan and in Western nations.

●Microwave Power Module (MPM)

The MPM combines the best aspects of TWT, semiconductor amplifiers, and state-of-the-art power supply technology into one package. This makes MPM into a good candidate for space application because it has high conversion efficiency, small size and low weight. C band (4 to 8 GHz) models exist.[19]

However, electron tubes require some kind of phase shifters. Compared to semiconductor devices, electron devices can deliver more power (several hundred watts). Delivering this power to the antenna, and associated issues, requires the development of phase shifters. It becomes necessary to distribute much power (tens or hundreds of outputs). If this cannot be done well, then much power is lost. This is a current issue.

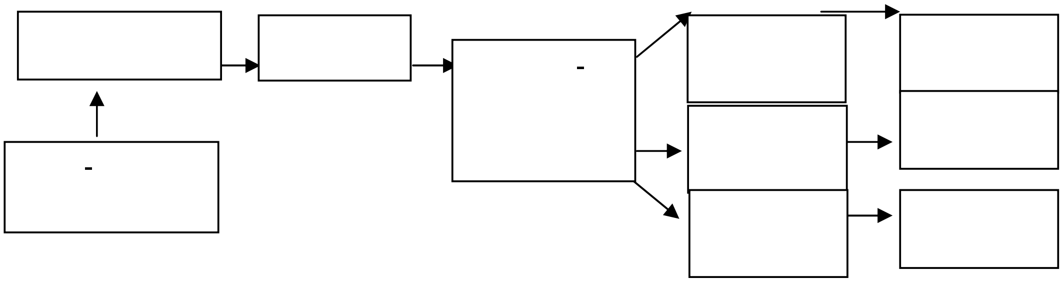


Fig. D.5.1 Microwave power transmission system using electron tubes.[16]

Even a high-power phase shifter is problematic because losses mount. It must be low loss, consume little electric power, be light, and be inexpensive to build. Here, it must be explained what is meant by "consume little electric power." Power is needed to turn the PIN diode "ON" used in a digital phase shifter. To turn "ON" a PIN diode, some current must be expended to avoid large losses. In the communications industry, wasting microwave energy is usually considered a major issue. However in the power generation industry, lost power is not a matter that can be ignored. More research shall be required to reduce waste and inefficiency.

(b) Semiconductor Microwave Transmitters

Characteristics of various transmitters are shown in Table D.5.4. The spectrum region between 2 and 4 GHz is called "S Band." Several cases were examined (space application,[20] to actual results[21]). In all cases, semiconductor transmitters seem light in weight, but closer study reveals that they are quite heavy with respect to the actual amount of microwave power they can deliver to the antenna. The biggest problem is that they have poor efficiency. Lighter transmitters can be realized using Microwave Monolithic Integrated Circuit (MMIC) devices, but these devices suffer heat-dissipation problems and other difficult technical issues. In the MMIC example below (10W, please refer to the table), the transmitter is very light (74.4g), but its efficiency is very poor (just 16%). Low power with high efficiency has been reported with the use of Silicon on Insulator (SOI) FETs. Gains of 18 dB and efficiencies exceeding 60 percent can be achieved at 2 GHz,[22] delivering 0.1W of output, and requiring a power supply of just 3 volts. Also, it is possible to realize a power-added efficiency ((PAE) = (P_{out}-P_{in})/P_{DC}) of 54%, and efficiency of about 60%, at 5.8GHz.[23] Unfortunately, the gain is low (9 to 12 dB). An efficiency of 40% is the best that can be expected using existing semiconductor technology, even though individual devices may look better or attractive.

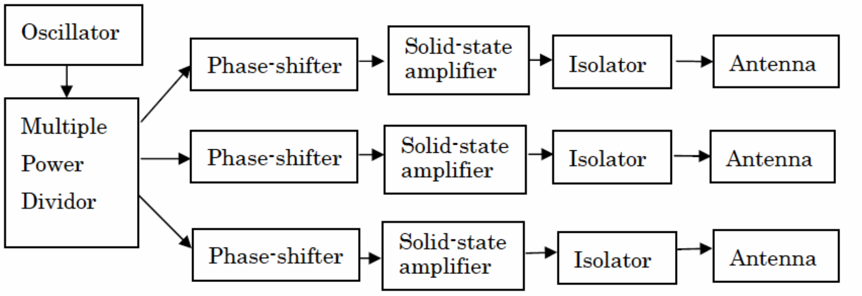
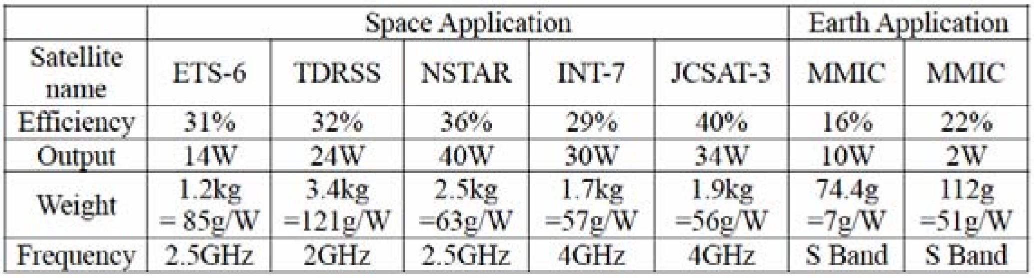


Figure D.5.2 Implementation of microwave transmission using semiconductors[16]

Table D.5.4 Characteristics of semiconductor Radio Transmitters[20,21]



	Space Application					Earth Application	
Satellite name	ETS-6	TDRSS	NSTAR	INT-7	JCSAT-3	MMIC	MMIC
Efficiency	31%	32%	36%	29%	40%	16%	22%
Output	14W	24W	40W	30W	34W	10W	2W
Weight	1.2kg = 85g/W	3.4kg =121g/W	2.5kg =63g/W	1.7kg =57g/W	1.9kg =56g/W	74.4g =7g/W	112g =51g/W
Frequency	2.5GHz	2GHz	2.5GHz	4GHz	4GHz	S Band	S Band

(c) Prospects for the future: More efficient microwave transmitters

DC-RF conversion efficiency of electron tubes is already at 65 to 75 percent. Compared with semiconductor methods, additional improvement will be very hard to achieve. However, it is conceivable in the next ten years to squeeze more efficiency out of magnetrons (used in microwave ovens) and TWT devices. With further research, 5% or more of improvement in efficiency is realizable. The best case currently for semiconductor technology is 40% (DC-RF conversion efficiency). Based on the current trend, drastic improvement is unlikely. The overall efficiency could be improved by re-configuration of amplifiers, as shown in Fig. D.5.4.

We also hope for a major breakthrough in SiC and GaN technology (high output, low weight).

D.5.3 Microwave antennas

1. Antennas for Transmitting Microwave Energy

As mentioned earlier, antenna design varies with the transmitter design. Here we shall concentrate on the antenna -- and put aside considerations of phase shifters. (Phase shifting is a large topic in itself.)

●Example 1

SPS2000[24] Slot Antenna with Cavity, 2.45GHz; thickness is 3.7cm; Density goal = 6.72 kg/ m^2. The term, “cavity-backed slot antenna” is often used.

●Example 2

1992 Japan Model [25] We project significant improvements for this antenna (2.45GHz, dipole antenna with reflector). We expect to slash the antenna element weight from 20g to 10g. The system (case plus heat radiator) consists of 64 elements. It would be 48cm ×48cm ×1mm ×2.69g/cc=620g in size and weight. Thus, 5.5kg/ m^2 could be realized.

Performance at 5.8GHz would also be pretty good. Assuming an antenna element spacing of 0.75λ=3.8cm, the same radiator size and weight density, and 160 antenna elements, one could get 9.6 kg/ m^2 with this design approach.

●Example 3

NASDA achieved 2.8g/m^2 for a Ka-band antenna. Features are 12 elements (parasitic elements), two layers, patch antenna, glass ceramics with ε_r =5, size of 5cm×5cm, and weight of 7g.

D.5.4 Beam Control

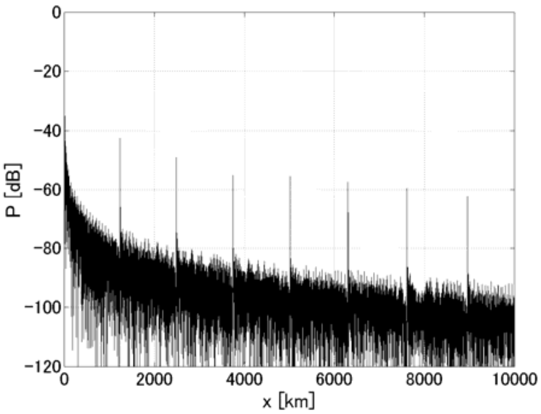
D.5.4.1 Interference reduction

Beam control is a fertile field for research. Good beam control is necessary for several reasons, including

(1) Maximize energy transfer to earth (reduce waste) and

(2) Limit unnecessary emission, so that existing telecommunication systems are not adversely affected.

For the "1980 Reference System," there was great concern about microwave radiation harming living systems. It was thus decided to limit radiation strength to 23 mW/cm^2 at the center of the beam, and that radiation should not exceed 1mW/cm^2 at the periphery of the rectenna site, where humans or animals may stray accidentally. There has been much debate about SPS harmonics affecting existing telecommunication systems (a debate slightly different from beam shape debates). However, in the past twenty years, this debate is also shifting quickly because of the sharply rising use of ISM band frequencies. As the radio spectrum is now used differently than in the past, a total system re-evaluation is appropriate. Fig. D.5.3 presents a beam pattern, power vs. distance from the center for a 5.8 GHz SPS (altitude 36,000 km, antenna size 2.6 km, and Gaussian taper of 10dB.) It illustrates the situation when the beam is deviated 0.016 degree (10km above the Earth) for a sub-array system, where the spacing is 1.5m, or 29 wavelengths. This figure reveals that there are serious problems with the sub-array configuration for the SPS --- there are "grating lobes" every 1,242 km., for instance. Since these unwanted lobes can interfere with telecommunication systems, this configuration is undesirable even if a retrodirective system that can respond to beam deviations swiftly and precisely is used.



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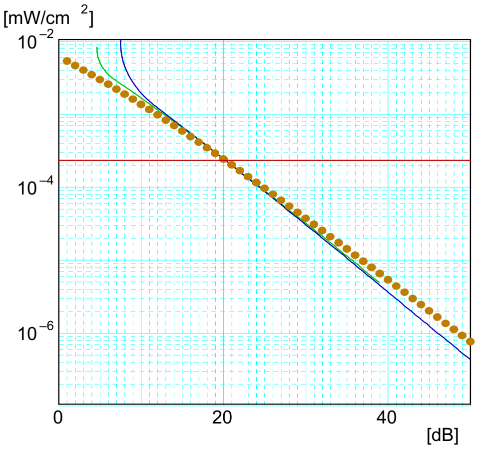


Fig. D.5.4 Power Density (10 km from center of beam) vs. Antenna Amplitude Taper[16]

Fixed antenna beam direction (without electronic steering) means that the direction of the transmitter antenna will be precision controlled, and the position of the SPS in space shall be controlled to the point of perfection. The result is that the center of the microwave beam will stay confined to within 0.016 of the center of the rectenna receiving region. This shall be promoted as an operational requirement of the SPS. Even when various constraints are applied to the beam, grating lobes (such as the ones that are conspicuous in Fig. D.5.3) are problematic. Therefore, the sub-array design approach faces a serious problem unless such a (mechanical) high-performance beam control system can be designed and tested.

Figure D.5.4 depicts the power density at a radius of 10 km from the center of the main beam as a function of antenna amplitude taper. If SPS is to operate inside the ISM spectrum and other terrestrial applications, like ETC (electronic toll collection system in Japan) and wireless LANs, then potential interference is always an issue.

Therefore, assuming that SPS must share frequencies with other microwave systems, then SPS must sharply reduce radiation falling outside of rectenna sites. This demands an SPS with a more sophisticated antenna design. If frequency sharing is required, then there must be more research, discussion, and debate on how much SPS radiation can be tolerated outside of rectenna sites. Clearly, this off-premise radiation cannot be reduced to zero.

D.5.4.2 Scan losses

Although it is possible to steer the beam in any direction by transmitter arrays, the range of scanning angles is limited by steering losses in real applications. If the angles exceed a certain angle calculated from the element spacing, grating lobes are generated. This means a significant loss since a considerable amount of power is transmitted in undesired directions. Even at smaller angles, reflections at antennas occur because of impedance mismatching due to the mutual coupling as a function of scan angle, θ. The scan-angle dependence of the voltage reflection coefficient, Γ, is shown in Fig. D.5.5.[26] The portion $(1-\Gamma^2)$ of the input power is sent to the antenna and Γ^2 is the reflection loss. In addition, when the beam is scanned to angle, θ, the radiation pattern is displaced from the broadside pattern. This scan loss has approximately $(1/\cos\theta)$ dependence. As a combination of the two factors, convenient typical scan loss curves are used.[27] They assume a scan loss in a $(1/\cos\theta)^n$ form, where $n = 3/2$ or 2.

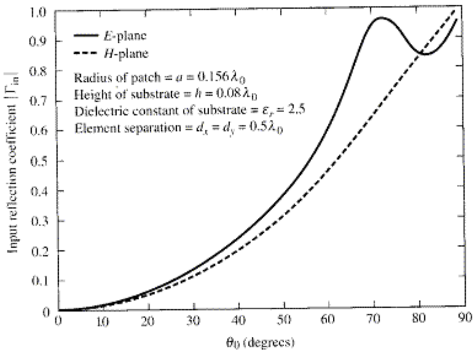


Fig. D.5.5 Typical magnitude of input reflection coefficient versus scan angle in E- and H-plane for an infinite array of microstrip patches (courtesy J.T. Aberte and F. Zavosh).[26]

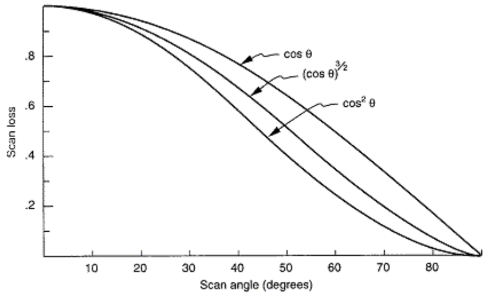


Fig. D.5.6 Typical scan loss curves.[27]

D.6 Rectenna and Ground Segments

D.6.1 Microwave Receiver (Rectenna)

The purpose of the "rectenna" (Rectifying Antenna) is to receive microwave power from an Earth-orbiting satellite and convert it to DC electricity. Such a system requires the following components.

(1) RF antenna
(2) Low-pass filter (stops re-emissions)
(3) Rectifier (diode circuit)

These are illustrated in Fig. D.6.1.

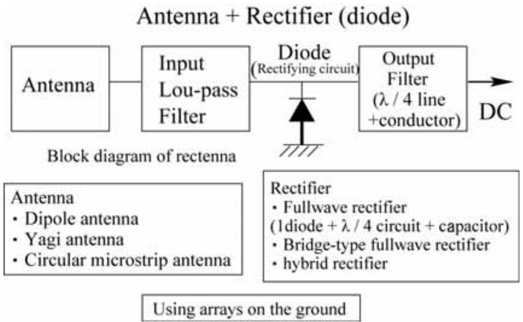


Fig. D.6.1 Layout of the basic rectenna[12]

As can be seen in Fig. D.6.1, various rectenna schemes have been proposed. In some cases, 70% efficiency can be achieved. However, the actual efficiency depends on various factors. In part, it depends on the microwave power input intensity. In other words, as the intensity increases, so does efficiency. However, it is also possible for intensity to be too high, causing efficiency to drop again. More R&D is needed to find an appropriate balance. Eventually, some compromise is needed because the received radiation is inherently strongest in the center of the beam, and weakest at the edge. Moreover, to be commercially viable, the rectenna must be "economically responsible." It must work for several years, must be economical to manufacture, economical to install, and economical to maintain throughout its entire life. One last requirement is that the rectenna must be "future proof." It must be designed with future contingencies in mind. If in future disposal and recycling are important issues, then the rectenna must be designed to meet those needs and requirements. Existing and future needs must be satisfied -- a tough proposition indeed.

D.6.2 Antenna Elements

The term "rectenna" is used because in the case a microwave power receiving station, "the antenna" cannot be considered as a separate entity. The design of the antenna affects the rectifier, and vice versa. It may be appropriate to consider this a traditional impedance-matching challenge -- matching the antenna with the rectifier. The following need to be considered.

1. size of each
2. shape of each
3. beam spread
4. gain
5. VSWR (Voltage Standing Wave Ratio)
6. characteristic impedance

It is necessary to minimize the VSWR so that power is transferred from the antenna to the rectifier. Reflections cause a great deal of trouble. All kinds of antennas are being considered: Dipole antennas, monopole antennas, microstrip antennas, print dipole antennas, and even parabolic antennas. Recently, there has been more creative ideas for locating large (several kilometers in diameter) rectennas. For example, large rectennas could be installed in forests or on the sea. In such cases, beyond electrical considerations, developers need to consider mechanical issues, sunlight penetration, wind issues, and other factors.

Deciding the total surface area of the rectenna requires careful consideration of the following factors.

1. The amount of microwave power that can be rectified
2. The power density of the incoming microwave radiation
3. Antenna gain

It should also be noted that the efficiency of the rectenna diminishes if the incoming power is too high or too low. Until now, rectifiers from a few miliwatts to a few watts have been developed -- depending on the rectenna configuration. This power range has been the most suitable or optimum. For rectenna sites studied by NASDA, the central region has been radiated at 160mW/cm^2. At 5.8GHz, there is data for the following two types of antennas:

1. Dipole antenna (with reflectors) about 6.7cm^2(=$\lambda^2/4$) and
2. Micro-strip antenna...... about 15cm^2(=$(0.75\lambda)^2$).

(depending on the design). Under these conditions, the applied microwave radiation becomes 160mW×(6.7 or 15) = (1.1W or 2.4W). From the rectifier's point of view, this is fairly high power. In this case, low gain would be better for the antenna. In contrast, one must have a high gain antenna to get the received power below 1mW/cm^2 in the perimeter of the rectenna site.

1. For a dipole antenna (with reflectors), the rectifier needs to be designed for power under 6.7mW.
2. For a micro-strip antenna, the rectifier needs to be designed for power under 15mW.

D.6.3 Rectifier Circuit

As there can be many kinds of antennas for the rectenna, there can also be many kinds of rectification circuits. Popular rectifiers include

(1) one diode plus quarter-wave circuit,
(2) full-wave circuit with capacitor,
(3) full-wave bridge rectifier, and
(4) rat-race rectifier circuit.

In addition, when combined with the power distributor, various combinations and designs are possible. The diode is the key component of the rectifier circuit of the rectenna. The maximum RF-DC conversion efficiency is largely determined by

1. dependency on input microwave strength (on the diode) and
2. dependency on connection load at the output (on the diode).

Of course, performance varies with exact circuit configuration of the rectifier, but the really important characteristics are

1. dc resistance,
2. stray capacitance,
3. turn-on voltage, and
4. breakdown voltage.

Until now, rectennas have generally used silicon Schottky barrier diodes. This is not because of its microwave characteristics but because of its transient build-up voltage is around 0.1 to 0.3 V --- much smaller than other diodes. Different types of diodes also have different breakdown voltages, but breakdown voltages in the range of 10 to 30V are becoming available.

There are two major research topics in the field of rectenna development. First, it is important to continue research into weak-wave microwaves, such as the sort that may be used in experimental power satellites and IC tags. Weak-wave means in the "micro-watt" range. This rectenna should somehow be integrated with the antenna, and if possible, a new diode ought to be developed. There should also be novel approaches to rectifier design. Second, there needs to be more investigation into connecting the rectenna to the power grid. The rectenna must be connected either in series or parallel. According to studies performed at Kyoto University, when the rectifier is connected to the grid, power transfer efficiency decreases by up to 10 %. Moreover, when the voltage is increased, the series approach performs worse than the parallel approach.

D.6.4 Microwave Reception --- Overall

The SPS systems designed to date have not been suitable for a country such as Japan, which has very little land available for such large engineering projects. If the transmitting antenna is about 2.6km in diameter, the receiving antenna can be held to less than 2 km, at 5.8 GHz. When transmitted from geostationary orbit, the beam intensity can be held to 159.6mW/cm^2 at the center, and to 1mW/cm^2 at the periphery. (Recently, this Figure has been improved to around 100mW/cm^2 for center of beam strength.) If the rectenna elements can be packed in at 0.75λ (=3.9cm), then the size of the system would be 2 km in diameter, and the system would contain 500 million elements. If the typical output of one element is 1W, 10V, 0.1A, then to get 1,000,000V, one-hundred thousand elements in series and ten-thousand circuits in parallel would be needed on the ground. As previously explained in the antenna section, the power received at the center and at the edge differs by more than two orders of magnitude. Accordingly, 1W、10V、0.1A is not viable for all elements. The number of elements therefore does not equal the number of connected elements.

In order to transfer more than 90% of the power from the SPS to the rectenna, there must be high-precision beam control. From the center of the rectenna, a pilot beam must be sent up to the SPS. Using information from the pilot beam, the SPS must perform "beam forming." This approach is called "retrodirective method." In the communications world, it is common for the downlink and uplink to use the same frequency band when retrodirectivity is employed. However, for the SPS, it is forecasted that the downlink will be in the range of 10^6 kW to 10^7 kW, five to six orders of magnitude greater than the signals used in the communications world. There are problems if the same frequency band is used. For a typical SPS situation, see Table D.6.1.

Table D.6.1 Typical parameters for SPS retrodirective system[28]

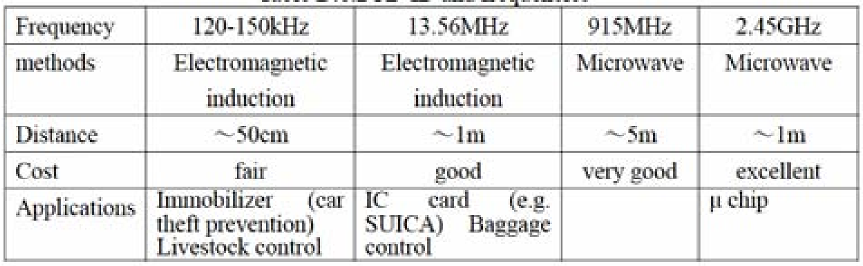
SPS Parameters	
SPS orbit	Geostationary orbit (36,000km)
Frequency	5.8GHz
Antenna diameter	2,580m
Power Transmitted to Earth (Total / one Element)	1340MW / 0.175W(22.4dBm)
Ground Station Parameters	
Pilot Signal Power (Pt)	1kW (60dBm)
Ant. Gain Gt (D=10m, η=0.7)	54dBi
EIRP	114dBm
Free Space Loss (36,000km)	199dB
Atmospheric loss	1dB
SPS Transmitter Antenna Element Gain Gr (Circular Microstrip Antenna)	6dBi
SPS Transmitter Antenna Element Received power (Pr)	-80dBm
Received Power Difference	102.4dB

Increasingly, we need to consider using different frequency bands, as the power differential is too great (over 100 dB), and there are problems associated with increasing distance between the uplink and downlink signals. However, at Kyoto University, we have tried experiments using spread spectrum techniques with the pilot signal, and the results are promising. More debate is needed on issues concerning the pilot signal. In any case, a meaningful pilot signal antenna for an SPS far in space must be something like a ten-meter-diameter parabolic antenna (at the center of the rectenna). Logically, a retrodirective pilot signal must be sent from the SPS to the dead-center of the rectenna, where the signal is reflected. A parabolic antenna 10m in diameter at the rectenna would waste a lot of space and power, roughly 120kW (160mW/cm2× 10mϕ). The pilot antenna (a parabolic antenna 10m in diameter) would have to be in the center of the rectenna. This would displace some surface area, equivalent to 120kW of power. For a 1 GW system, this represents a loss of 0.01%, this is an economic issue that can be solved. More difficult is the engineering issue: The pilot antenna is transmitting power to the SPS. In the opposite direction, microwave radiation of about 84kW (=120kW×0.7) is being transmitted from the SPS. This could damage the pilot system. Ways of improving this situation must be discussed more. One possible remedy is offset the downward beam so that the center is not on the center of the rectenna. The pilot system would then absorb less radiation from the SPS.

D.6.5 Recent trends in rectenna research

A recent close system of the UPS is RF-ID. The RF-ID is based on a chip. This chip contains information, and power that can be supplied by radio waves. The most common application of the RF-ID is a verification system. This is also called an "IC tag" and is receiving attention all over the world, in the form of standardization and research. We can apply the rectenna technology to the rectifier of the RF-ID (Table D.6.2).

Table D.6.2 RF-ID and frequencies[29]



Frequency	120-150kHz	13.56MHz	915MHz	2.45GHz
methods	Electromagnetic induction	Electromagnetic induction	Microwave	Microwave
Distance	～50cm	～1m	～5m	～1m
Cost	fair	good	very good	excellent
Applications	Immobilizer (car theft prevention) Livestock control	IC card (e.g. SUICA) Baggage control		μ chip

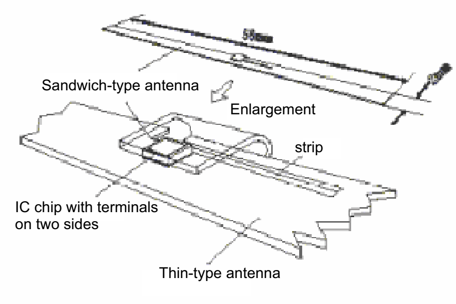


Fig. D.6.2 μ-chip antenna[30]

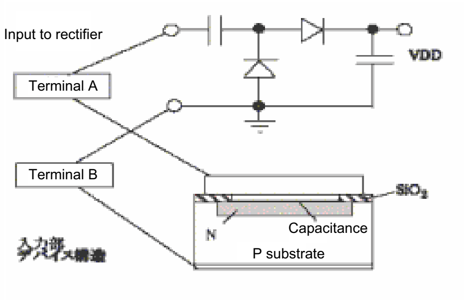


Fig. D.6.3 μ-chip rectifier[30]

Presently, most RF-ID research is occurring in the 915 MHz band. RF-ID is still in the developmental phase. If energy exchange becomes necessary for RF-ID, then microwave would be best. However, within the range of existing investigation, only communication needs are being studied. Hitachi has come up with a micro-chip operating near 2.45GHz. It is a super-miniature RF-ID chip. It has dimensions of 0.4mm×0.4mm×0.06mm, and is being pursued so that it can be inserted into a sheet of paper. The rectenna part of the μ chip is shown in Figs. D.6.2 and 3.

To those ends, research is starting to develop rectennas that exhibit high efficiency at low power for the same reason that only weak power can reach experimental power satellites in orbit. CRL has released some findings on weak-power rectennas designed for experimental power satellites.[31] In the literature, one can find a rectifier with even higher efficiency with weaker microwave input (Fig. D.6.4). This was achieved by getting the antenna part large (a parabolic antenna was used as shown in D.6.5) and thus raising the microwave power input to the rectifying circuit. Using this approach, high efficiency is achieved using relatively weak input.

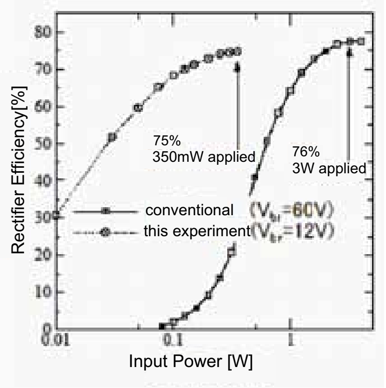


Figure D.6.4 Improving rectifier efficiency with low-power microwave[31]

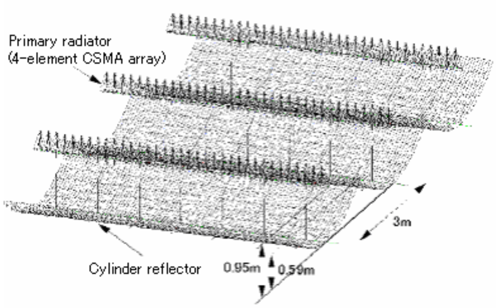


Figure D.6.5 Enlarging aperture to improve rectifier efficiency.[31]

D.6.6. Topics concerning the commercialization of rectennas

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There is more and more discussion of the commercial applications of rectennas, but the applications are hindered by the following issues.

(a) Absorption of microwave

- There is some performance degradation when the rectenna gets wet (salt spray, rain water, etc.).
- Various extraneous substances can adversely affect the performance of the rectenna (e.g., dirt, unexpected particles, animal nests, snow, and frost). These problems occur in outdoor situations.
- To mitigate the aforementioned problems, protective covers become necessary. These covers can adversely affect the radio properties of the rectenna, but the economic consequences need to be considered.

(b) Stability of SPS as an energy source

Because the rectifier output is derived from received microwave radiation, the output is potentially disrupted by changes in the received radio radiation. To be commercially viable, the rectenna must guarantee certain requirements (voltage and power).

(c) Microwave re-emission

Microwave arriving at the rectenna from space could be bounced off and cause serious interference to other electrical systems in case of malfunction of a rectenna system. The problems generally occur when equipment uses the same frequencies or when secondary emissions occur. The unwanted emissions can be suppressed with filters. Unfortunately, the cost of the filters is currently high. If possible, rectennas must be designed without costly filters.

D.6.7 Ground Network

It is widely assumed that a commercially feasible SPS would be on the order of 1,000 MW. SPS is not small peanuts (such as wind and tidal power). It would deliver significant electric power and would contribute greatly to any national power grid. The technology for connection to the grid exists, although the output of the SPS is direct current. The output of thermal and nuclear power plants is AC because they must first drive a turbine-generator of some kind. (Note that the SPS ground station has no moving parts. This translates into low maintenance costs.)

(a) Evaluation: Influence of Being Steady State

As noted above, SPS has no moving parts. We foresee no problems (economic, technological, etc.) with connecting the SPS to a national power grid because the SPS is a "steady-state" system. The output is predictable. Moreover, a gigawatt class power plant is similar to a nuclear power plant or large hydropower plant. Most grid connection issues, therefore, are the same. The SPS is similar to a nuclear power plant in that it provides "base" power to a power grid; SPS is not intended to meet fluctuating power needs (daily, seasonal, or otherwise). SPS does have some "down time" (seasonal blackouts due to eclipses), but these situations can be compensated with back-up thermal systems.

(b) Evaluation: Effects of SPS-related Accidents or Malfunctions

It is presumed that the SPS is a power source that is put into service into a national power grid (electric power generation and power distribution system). The SPS becomes "on line." Accidents can occur at.

1) the SPS side or
2) the grid side.

It is felt that a large power source, such as the SPS, is not really a new situation for power utility companies. The grid is designed to take up the slack if the SPS drops out without warning. For example, hydropower plants can increase output to cover temporary losses. (For example, release more reserve water.) In some cases, the output of the rectenna may lapse. However, the DC power converter may be able to handle these lapses in most cases, within a certain specified range of lapses. If the lapse or power failure is too large, then output may cease. If connected to a large national grid, then the grid should be able to take up the slack. If an accident occurs on the grid side, there is potential for trouble for the rectenna (power source to the grid). The grid may get hits from electrical storms (thunder storms), but the power failure duration should be very short, short enough for the SPS to manage with such hits to the grid. However, a major accident at another power source (resulting in an output failure for hours or days) may be difficult for the SPS to cope with. More careful study is needed on this matter.

In summary, connecting a 1000 MW class SPS ground station to a power grid should present no serious problems. Any problem can be dealt with by state-of-the-art technology. However, several issues require more precise study (issues of "degree").

D.7 Economics of SPS

SPS economics is evaluated based on JAXA 2003 model as an example.

D.7.1 SPS Cost Model

(1) Creation of 03M Cost Model

(a) Structure of 03M Cost Model

The intent of the 03M Cost Model is to facilitate the cost calculations for deploying and operating the SPS. The main cost considerations are

(1) the space segment,
(2) the ground segment (rectenna),
(3) launch expenses, and
(4) maintenance expenses.

●Space segment

This discussion considers the cost of manufacturing the 2003 Model (whose configuration is discussed elsewhere). This model has four major parts.

1. Primary Mirror
2. Secondary Mirror
3. Conversion Module (contains solar panels and microwave power transmitters)
4. Support structures for all of the above

The Conversion Module consists of sunlight-to-DC converters and DC-to-microwave converters, and a supporting system. The sunlight-to-DC converter is relatively easy to calculate when the cost per unit area is known, and the total area required is known. In a similar way, it is not difficult to calculate the cost of the microwave power transmitter. The technology is available, and the cost is well known.

●Ground segment (rectenna)

Costs associated with the construction of the rectenna are segmented as follows.

(a) microwave reception part,
(b) support structure for it, and
(c) connection to the power grid on Earth.

The cost of the microwave-to-DC conversion can be calculated by multiplying the cost per unit watt (say, one dollar per watt) by the power requirement (say, 1000 MW). The power requirement also establishes the area of the rectenna. The costs to achieve this area (land acquisition, construction cost, and so on) can then be calculated. When the power requirement is established, then many things can be nailed down.

●Launch expenses

There are two components:

RLV (Reusable Launch Vehicle)	Cost X
OTV (Orbit Transfer Vehicle)	Cost Y
Total launch expenses	Cost X plus Cost Y

The RLV is used to transport material to low-Earth orbit, where some assembly takes place. An OTV (for example, an electric propulsion vehicle) is assumed to be used to lift the SPS from low-Earth orbit to final orbit (geostationary Earth orbit).

●Maintenance costs

Maintenance costs of the space segment can be calculated as a fixed percentage of the construction costs of the space segment. Maintenance costs of the ground segment can be calculated as a fixed percentage of the construction costs of the ground segment. Figure D.7.1 shows the calculation flow of the 03M Cost Model

(2) Result of Calculations

The results explain the costs associated to build a 1 GW SPS.

(a) O3M Cost Model

The costs to build a one gigawatt system are summarized in Table D.7.2. In this model, we seek to minimize weight. In order to achieve this, we assume that there is no concentration of solar radiation on solar cells; the concentration factor is 1.0. This can be easily raised to 2.0, but then the solar cell requires a cooling mechanism. This would be a radiator of some kind. The weight of the radiator would be 2.00g/W. As you can see from this table, a 1 GW SPS would cost 1.29 trillion yen. This cost would be recovered by charging 8.9 Yen/kWh to the buyer of the electricity.

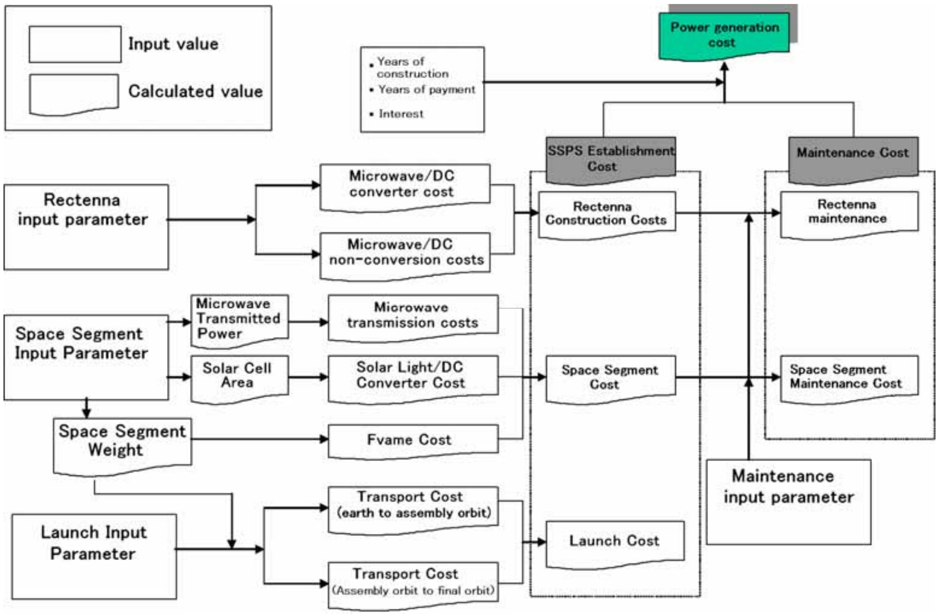

Fig. D.7.1 Flow chart of 03M Cost Model

Table D.7.2 Results for the 03M Cost Model

1)	Received microwave power	1.32	GW
2)	Transmitted microwave power	1.34	GW
3)	Collected power	1.79	GW
4)	Output of solar panel	1.79	GW
5)	Amount received by solar panel	10.70	GW
6)	Amount received by the front end	13.37	GW
7)	Area of the front end	9.88	sq.km.
8)	Area of the transmitter	7.91	sq.km.
9)	Area of its antenna	7.91	sq.km.
10)	Exhaust heat from misc. sources	6.68	GW
11)	Exhaust heat from solar panel	6.72	GW
12)	Exhaust heat from transmitter	0.18	GW
13)	Weight of the front end	2,000	tons
14)	Weight of solar panel	1,186	tons
15)	Weight of microwave transmitter	2,685	tons
16)	Weight of its antenna	2,372	tons
17)	Weight of heat releasers	0	
18)	Weight of the support structures	624	tons
19)	Secondary mirror	800	tons
20)	Weight of one Conversion Module	6,867	tons
21)	Weight of entire space segment	9,667	tons
22)	Cost of emitting microwave energy	6,713	million Yen
23)	Cost of converting sunlight to DC	1,581	million Yen
24)	Cost of support structure	203	million Yen
25)	Cost of entire space segment	8,497	million Yen
26)	Diameter of rectenna	1.56	km
27)	Microwave-to-DC converter	1,000	million Yen
28)	Other ground expenses	637	million Yen
29)	Total ground expenses	1,637	million Yen
30)	Amount that must be lifted into space	12,745.55	tons
31)	Number of RLV sorties	255	
32)	Number of RLVs needed	6	vehicles
33)	Total launching fuel needed	290,004	tons
34)	Operational costs of the RLVs	2,206	million Yen
35)	Cost of building the RLVs	255	million Yen
36)	Maintenance costs of the RLVs	0	
37)	Total cost of launch fuel for the RLVs	133	million Yen
38)	Force requirement of the OTV	2,827.85	N
39)	OTV power needs	86.66	MW
40)	mass ratio[32]	0.91	
41)	OTV power supply mass	1,733.23	tons
42)	OTV propellant mass (one way)	1,121.25	tons
43)	OTV propellant mass (round trip)	1,345.51	tons

44)	OTV initial total mass	3,078.74	tons
45)	Operational costs of the OTV	97	million Yen
46)	Manufacturing costs of the OTV	6	million Yen
47)	Maintenance costs of the OTV	91	million Yen
48)	Propellant costs of the OTV	7	million Yen
49)	Transportation costs (from earth to LEO)	2,594	million Yen
50)	Transportation costs (from LEO to GEO)	200	million Yen
51)	Total transportation costs	2,794	million Yen
52)	Annual maintenance expenses	271	million Yen / year
53)	Energy delivered to power grid	8,322,000,000	kWh each year
54)	Real interest rate	5.2215	%
55)	Construction cost of the SPS	12,929	million Yen
56)	Power generation unit cost	8.8963	Yen / kWh

Note 1 Front end means "primary mirror system." It is a rotating system and directs sunlight to the solar cell array.

Note 2 All costs are one-time costs incurred to realize one operational SPS. "Operational cost" does not refer to the cost of operating the SPS. Rather, it is the cost of getting the system completed.

(b) Model for Burden on the Environment

The following explains that SPS is very friendly to the environment with respect to carbon dioxide emissions into the atmosphere. Refer to Table D.7.3 to see how much carbon dioxide is emitted to produce electric power. SPS releases less CO2 into the environment than wind power and nuclear power. SPS is an extremely clean source of energy.

Table D.7.3 CO2 Emissions of the SPS project

Amount emitted to manufacture the space segment	83,160	tons of CO2
Amount emitted to lift it into space	959,527	tons of CO2
Amount emitted to manufacture the rectenna	953,710	tons of CO2
Amount emitted to operate the space segment	31,281	tons of CO2 per year
Amount emitted to operate the rectenna	9,537	tons of CO2 per year

Consequently, an SPS releases 12.10g of CO2 into the environment to generate one kWh of electricity.

(c) Model for "EROI" (Energy Return on Investment)

To make money, money must be spent. In the financial world, this is called "ROI" (Return On Investment). In the same way, to make energy, energy must be expended.

This can be called "EROI," or "Energy Return on Investment." Solar cells have a very poor EROI. A massive amount of energy is needed to produce them, and it takes a decade for them to return that energy. Using solar cell power to manufacture solar cells is not a winning proposition. However, SPS is a much better proposition, from the point of view of resource utilization. Consider the data in Table D.7.4.

Table D.7.4 Energy payback time required for SPS

Energy invested to manufacture the space segment	1,622	GWh
Energy invested to lift it into space	2,151	GWh
Energy invested to manufacture the ground segment	548	GWh
Energy to keep the space segment operating	113	GWh/year
Energy to keep the ground segment operating	5	GWh/year
Total invested energy	7,762	GWh
Total Energy Return on Investment	262,800	GWh
Energy Return on Investment	33.86	
Energy Payback Time	0.89	Year

(4) Summary future agenda

The new model (Year 2003 Standard Model for SPS) was evaluated for cost effectiveness, cleanliness (amount of carbon dioxide emission), and EROI (Energy Return on Investment). Although this report does not go into detail concerning the Parameter Study, some parameters were examined by some investigators. No progress can be made if all parameters are "loose." Some must be fixed (to default values) so that analysis can be carried out. With more time, the default values can be re-considered. However, an infinite amount of time is not available. To realize the SPS in the 2020 to 2030 timeframe, much more work and study must be performed.

There is still a great deal of uncertainty in space launch issues. One issue is exploring means of reducing launch cost.

We are considering matters such as how much mass can be accommodated by RLVs and OTVs, as well as specific means of transportation between low-Earth orbit and GEO (namely, is all assembly work completed at low-orbit and then pushed to GEO, or is some assembly work performed at GEO position). Any approach has its pros and cons. More discussion between working groups will facilitate better understanding on how to control cost, and increase construction speed and transportation speed.

D.8 Environmental and Safety Matters

(1) Current thinking

The deployment and the operation of the SPS involve some risks and hazards. The following three topics need to be tracked carefully by parties concerned.

- The environmental and safety-related risks imposed by the SPS on external parties.

This is discussed in detail below.

- The environmental and safety-related risks imposed by external parties on the SSPS.

This is discussed in detail below.

- How to respond in the case of accidents and system malfunctions.

This is discussed in detail below.

Note: JAXA models are developed with NASA reference systems in mind.

Tables D.8.1 and D.8.2 summarized the various issues currently being tracked with respect to risks and hazards. The first table concerns SPS's affect on externalities; the second table concerns the reverse situation.

(These two tables include responses to accidents and malfunctions, so there is no separate table for accidents and malfunctions.)

Table D.8.1 Environmental and Safety Issues of SPS (SPS's affect on external parties)

Issue	SPS Deployment Phase	SPS Operational Phase
Transportation		
RLV lift, and return	O	O
OTV (	O	O
Assembly and Maintenance	O	O
Microwave power transmission		
Affect on other spacecraft		O
Affect on the atmosphere		O
Affect on the ionosphere		O
Affect on aircraft		O
Affect on animals flying in the beam path		O
Affect on communication systems		O
Affect on medical systems		O
Affect on terrestrial life		O
Space segment		
Affect on other spacecraft		O
Consumption of arth resources	O	O
Rectenna (Ground segment)		
Affect on power transmission systems		O
Affect on installation neighborhood		O
Release of heat		O
Re-emission from rectenna		O

Table D.8.2 Environmental and Safety Issues of SPS (affect of external things on SPS)

Issue	SPS Deployment Phase	SPS Operational Phase
Space segment		
Debris collision	O	O
Space environment	O	O
Acts of terrorism		O
Ground segment		
Local environment		O
Electric power systems		O
Acts of terrorism		O

(2) Environmental and Safety Issues of SPS (SPS's affect on external parties)

(a) Transportation

1) Effects of RLV (Reusable Launch Vehicle) on the atmosphere and ionosphere

(3) Environmental and Safety Issues of SPS (The affect of external things on SPS)

In NASA's reference system, two lift systems are considered: (1) HLLV (Heavy Lift Launch Vehicle) and (2) PLV (Personnel launch vehicle). NASA considers the use of methane (CH_4) and oxygen (O_2).

However, in this study, only hydrogen (H_2) and oxygen (O_2) are considered. Therefore, in this study, we omit concerns for carbon dioxide (CO_2), and we only concern ourselves with the effects of water (H_2O) and hydrogen gas (H_2).

RLVs emit water and hydrogen gas. This can negatively affect local weather in the lower atmosphere, but is relatively minor.

A matter for different concern is the negative effect RLV chemical emissions have on the ozone layer. (The ozone layer shields the earth from solar ultraviolet radiation.) While solid-fuel rockets often use chlorine compounds, RLVs only emit hydrogen gas and hydroxyl group chemicals. These have a minor effect on the ozone layer.

It is possible for water and hydrogen emissions from RLVs to have a negative effect on the ionosphere, especially the F layer. This may have some negative effect on telecommunications.

2) Effects of OTV (Orbit Transfer Vehicle) on space environment (above the atmosphere)

Currently, the OTV of choice is the “ion thruster.” Therefore, we need to consider the chemical emissions of the ion thruster and how it may affect the space environment. More study is required.

(b) Deployment and maintenance

It is important that as little as possible debris be released into space. Documentation exists on this topic (space debris control standards).

(c) Transmission of microwave radiation

1) Effect on other spacecraft

The primary concern here is how microwave radiation that is beamed from the SPS to its Earth station can adversely affect the performance of other equipment working in space. The purpose of SPS is to deliver electric power to Earth. The main function of other things in space is space-to-space and space-to-Earth electromagnetic communications. Hence, there are issues of electromagnetic susceptibility and EMI.

We considered the ramifications of SPS radiation on other spacecraft, from the EMI perspective. However, we did not consider the ramifications of SPS radiation on humans working in space. For example, there could be humans working inside the International Space Station (ISS).

a) Affect on instrumentation

Microwave radiation emitted by the SPS may adversely affect the performance of electronic instrumentation on other spacecraft in orbit around the Earth. This interference would largely be electromagnetic interference in nature.

Several nations have standards concerning EMI in space. However, the SPS will adhere to the requirements of MIL-STD-461C ("MIL spec" of the United States Department of Defense) shown in Table D.8.3.

Table D.8.3 Limits of EMI upon Spacecraft Instrumentation (MIL-STD-461C Part 3)

Spectrum range	Electric Field Strength (V/m)	Radiated Power Density (mW/sq. cm.)
14kHz-30MHz	10	0.03
30MHz-10GHz	5	0.007
above 10GHz	20	0.11

b) Explosives

Occasionally, explosive devices are required to do work in outer space. For example, explosive bolts are needed to deploy antennas and large solar panels. Explosives are also needed to transfer from LEO to a geostationary orbit (e.g., solid-fuel booster rocket). Controlled explosions are unavoidable, but uncontrolled explosions must be avoided. SPS will adhere to applicable standards, such as MIL-P-24012 and JIS W 7005 "Aerospace Systems Requirements."

c) Orbit of artificial satellites

Geostationary orbit positions are very popular. There are many kinds of geostationary satellites: telecommunications, TV broadcasting, weather observation, Earth observation, and so on. SPS will also require a geostationary position in space. Once in position, it will beam down electric power around-the-clock. This beam path must be internationally recognized and other users of outer space must take care to avoid this beam. This beam may affect other satellites being launched, or affect satellites in operation.

Fundamentally, the beam only exists between the SPS and its ground station. However, sidelobes may present problems to other users of outer space. Therefore, coordination with other parties is necessary. International bodies should understand the needs of SPS as well as the needs of other users of outer space. These various needs need to be balanced for optimum benefit to people living on Earth.

It is difficult to please everyone. Various nations have various launch facilities located around the world (in South America, in Africa, and so on). Their launch activities will need to be coordinated with the mission of the SPS. Their launch vehicles may pass through SPS beams. To avoid electromagnetic interference between SPS and other artificial satellites in orbit around the Earth, antenna radiation patterns and drift from their assigned positions in orbits of satellites and SPS must be taken into account.

2) Affect on the Earth's atmosphere and ionosphere

The realization of SPS faces many issues. One major issue is the affect of SPS on the Earth's atmosphere and ionosphere. Many effects on the ionosphere are conceivable. There might be plasma wave excitation. The net effect is that radio communications may be adversely affected. In contrast, the attenuation of microwaves by the atmosphere is a concern at higher frequencies.

D.9 Study of Laser-based SPS[33]

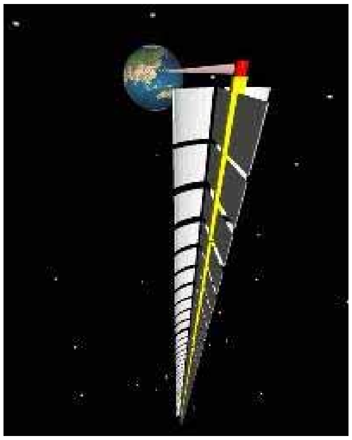

Fig. D.9.1 L-SPS concept (©JAXA, 2004)

Another recent major advance in JAXA's SPS study was the creation of a system concept for a laser-based SPS (L-SPS). Figure D.9.1 illustrates the proposed concept of L-SPS. The concept of a laser-based SPS is relatively new, and a system concept for it was only recently proposed within JAXA. The proposed L-SPS consists of cascaded elements called L-SPS units. Each L-SPS unit consists of solar collection mirrors, a solar-pumping laser unit, and radiators. Each L-SPS unit will be on the order of 200 m (W) x 200 m (D) x 100 m (H). Since 100 L-SPS units will be connected in series; the entire L-SPS will be similar to a pencil-type satellite.

D.9.1 Laser power transmission

The laser-based SPS (L-SPS) is relatively new in Japan, but the microwave-based system has a long history of R&D. JAXA is conducting a study of a direct solar pumping laser system with the Institute for Laser Technology (ILT) and the Institute of Laser Engineering at Osaka University. Direct solar-pumping laser generation has an advantage over conventional solid state or gas lasers that use electrical energy to generate laser oscillation. If the laser oscillation is generated by the laser diode or in some other way using electricity, then the overall efficiency of the L-SPS will be low, since the solar energy must be converted to electricity using photovoltaic cells or some other low-efficiency method. Recent advances in the technology of direct solar pumping laser generation have shown the possibility of highly efficient energy conversion and transmission, in comparison with microwave-based power transmission.

D.9.2 Direct solar pumping laser oscillation

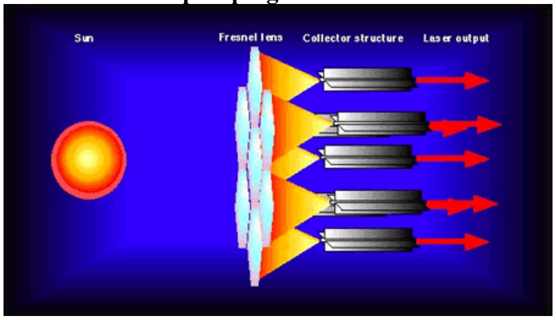

Fig. D.9.2 Basic concept of laser-based SPS

Fig. D.9.3. Experimental setup for direct solar pumping laser oscillation

In order to generate a laser beam by direct solar pumping, the highly concentrated solar energy must be injected into the laser medium. The minimum required concentration ratio will be determined mainly by the size of the laser medium, the solar energy absorption ratio and the thermal shock parameter (i.e., weakness of the material to internal stress caused by an internal thermal gradient). There are several types of materials that can be used for the laser medium. From the standpoint of resistance to thermal stress, sapphire is the optimal material for the laser medium. However, it is not easy to make a large sapphire crystal. Therefore, we decided to use a YAG (yttrium aluminum garnet) laser crystal, since a YAG crystal is easier to make than a sapphire crystal. When a YAG crystal is used, the required solar compression ratio will be at least a few hundred.

Figure D.9.2 presents the basic concept of a solar power system based on direct solar pumping. It consists of solar concentration lenses and a laser medium with thermal radiators.

Figure D.9.3 depicts an experimental setup for direct solar pumping laser oscillation that demonstrates the proposed concept. Recently, JAXA and ILT successfully generated a laser beam by direct solar pumping, using simulated solar light and a fiber laser medium made from a neodymium-chrome doped yttrium aluminum garnet (Nd-Cr:YAG) crystal.

Studies of other types of laser media, such as disc type bulk crystal, are also in progress at ILT. The conversion efficiency from the input power to the output laser power achieved in this experiment was 37%.

D.9.3 Design of the solar pumping laser system

In designing a solar pumping laser system, the removal of heat from the laser medium is important, since only part of the injected solar energy will appear as laser output. The remaining energy will merely generate heat. When highly concentrated solar light is injected into a laser medium, roughly one third of the injected solar energy will appear as laser output. Another one third of the injected solar energy will generate heat. This energy increases the internal energy of the laser medium but does not appear as laser output. The remaining one third does not contribute to laser oscillation because its spectrum is so far from that of the laser output.

The solar energy in the unusable portion of the spectrum should be not be injected into the laser medium. Polymer film with a selective reflectance ratio depending on the wavelength will be used to reject the unusable portions of the spectrum.

D.9.4 Reference model of L-SPS

A reference model of L-SPS was proposed in order to accelerate study of the individual technologies needed to realize the L-SPS. Figure D.9.1 illustrates the proposed L-SPS, which will have an output power of 1 GW. The capability of the heat removal and radiation system limits the potential output of the L-SPS. The L-SPS consists of hundreds of small L-SPS units that each have 10 MW of output power. These L-SPS units are connected in series. Each L-SPS unit consists of a pair of solar energy collection mirrors, a laser module that houses the laser media, and thermal radiators, as in Fig. D.9.4. The primary solar collection mirrors will be 200 m in width in order to collect the necessary solar energy. Reflected solar light is formed into a concentrated solar beam one meter in diameter at the secondary optical system, and then injected into the laser medium. Each laser medium is cooled by liquid coolant. Heated coolant will be moved to the thermal radiator to dispose of the heat. Figures D.9.5 and 6 present examples of the layout of the laser media and optics. Research into other types of laser media such as a fiber medium is also being conducted in order to determine the best medium for the laser module.

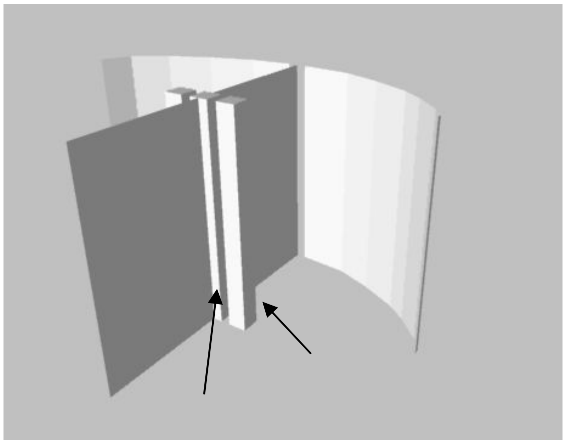

Fig. D.9.4 Concept for L-SPS unit

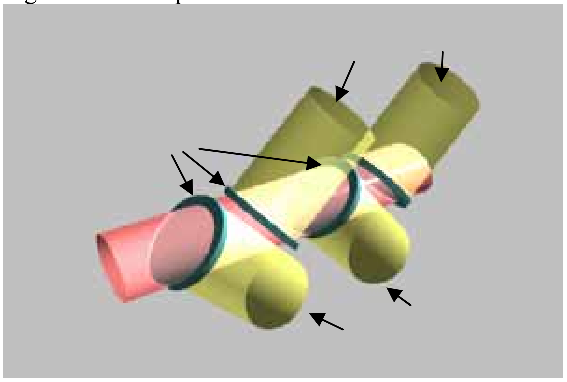

Fig. D.9.5 Layout of the solar pumping laser (disc type)

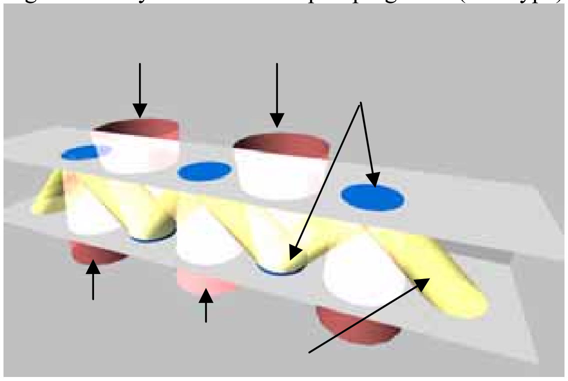

Fig. D.9.6 Layout of the solar pumping laser (active-mirror type)

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=(number density of atom)×(satellite velocity×(time interval)

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Appendix E European activities (ESA reports)

Solar Power from Space – A Space Contribution to Options for 21st Century Sustainable Energy Systems

Abstract- Terrestrial solar power is one of the fastest growing energy sectors with high growth rates sustained over more than a decade (especially in Europe) and very promising forecasts.

Since 30 years the idea of a large solar power plant in Earth orbit, transmitting energy to Earth-bound receiver sites enjoys periodic attention from energy and space entities. All studies concluded the principal technical feasibility of the concepts and gradually improved their power to mass ratio. No substantial development efforts were undertaken however since with current technology space generated electricity costs would still be too high, upfront costs prohibitive and the launcher sector not mature enough to reduce €/kg to orbit costs by the required order of magnitude.

In the past space concepts were mainly compared to traditional energy systems. Based on this background, the Advanced Concepts Team (ACT) at the European Space Agency started a three-phased programme in 2003. The first phase of the programme, the Validation Phase, focused on a comparison of space solar power plant with comparable terrestrial solutions on the one hand and the assessment of the potential of SPS for space exploration and space application on the other.

Space concepts were compared to terrestrial solutions based on equally advanced technology and equal economic conditions for the timeframe 2020/30 in terms of energy payback times, final €/kWh generation costs, adaptability to different energy scenarios, reliability and risk.

E.1 Introduction

Space as well as energy are currently perceived as sectors of not only strategic but also increasing importance for this 21st century. Traditionally, they are connected by only weak links.

One of the fundamental issues to be resolved seems to be the identification and implementation of a sustainable energy system, capable to supply the increasing global energy demand necessary to sustain living-standards of developed countries and the development and rise of living-standards of developing countries. The availability of cheap and abundant energy plays a crucial role in enabling the reduction of poverty and development gaps.

The analysis of the evolution of our energy system shows that it underwent several times in the past radical changes (e.g. introduction of electricity, oil and gas, nuclear power) despite its inherent inertia. All of these changes were predictable several decades before their occurrence since they were based on discoveries, the demonstration of their principal feasibility and the subsequent identification/ emergence of needs. Solar power from space was proposed several decades ago, all studies have shown their principal feasibility and the increasing adverse implications of fossil fuel seem to demonstrate the need for a change.[1]

This article tries to contribute to the search for feasible options to be considered for long-term energy systems for this century.

E.2 Motivation and Frame

In 2003, the Advanced Concepts Team (ACT) of ESA has started a multiyear program related to solar power from space. The outcome and findings of the first of the three phases of the program will be presented in this paper. The first phase was dedicated to the assessment of the "general validity" of space concepts for Earth power supply as well as for space exploration applications.[2, 3] This paper will focus on the space-to-Earth concepts.

The motivation for the European SPS Programme Plan may be divided into a global and a European dimension.

E.2.1 Global Scale

On a global, long-term scale, there seem to exist three major parameters to be considered in connection with the energy system for the 21st century and beyond.

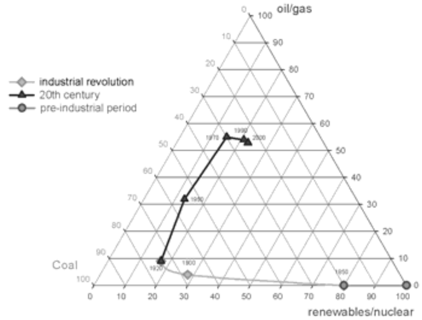
First, according to past experience and all current projections, the global energy need will continue to rise in close connection with the increasing world population.

Second, energy availability and use is closely connected to living standards and development levels, notwithstanding significant regional influence due to climatic conditions and lifestyle. Currently, the average primary energy consumption per capita worldwide is about 17 000 kWh/year. It is more than 5 times higher in North America (100 000 kWh/year) but only 4 and 10 kWh/year for the worldwide most numerous and fasted increasing populations, in Africa and Southeast-Asia respectively.[4]

Therefore, if the natural increase of the total power consumption due to population development should be accompanied by an increase of average living standards in developing countries, the total power need will increase accordingly faster.

Third, a significant part of the global emission of greenhouse gases (GHG) stems from the production of electricity (40%) and from transport (21%). Despite the continuous decrease of carbon intensity over the last 30 years, the decrease has not been and will probably not be sufficient to stabilize or reduce the total CO_2 emissions due to the stronger increase of the total power consumption. According to the International Energy Agency, worldwide carbon-dioxide emissions will rise to $38 \cdot 10^9$ tons per year from currently $16 \cdot 10^9$ tons (increase of 70%).[4]

In addition, new energy needs are likely to alter the situation: one of the currently foreseeable factors is the gradual increase of the fraction of global population subject to severe fresh water stress. Energy-intense desalination plants will be part of the solution to this problem.



2 1

Health issues due to metropolitan pollution levels caused by fossil fuel based traffic are likely to add additional arguments for a change of the global energy system.

When trying to anticipate developments, trends derived from past evolution might give valuable indications. Plotting the proportional supply share of 1. renewables/nuclear sources, 2. coal and 3. oil and gas (Figure E.2.1), shows the gradual change of our main energy sources from those with very high carbon content (biomass, coal; until end of industrial revolutions) to oil and gas for the remaining 20th century.

Since the 1st World War, the share of coal decreased steadily from an all-time high of about 70% to the benefit of oil and gas, the fuel of the transport industry. To a lower extent, the oil crisis of the 1970s had a similar effect, when the introduction of nuclear energy lead to the leveling of the oil and gas share at about 60%. Currently a trend from oil to gas is observed (not shown in Figure E.2.1), in line with the successive reduction of the carbon content of fuel. (C:H ratios: wood: ~10:1, coal: ~2:1, oil: ~1:2, gas: ~1:4)

Extrapolating this trend, the curve will approach the lower right corner of the triangle shown in Fig. 1, dominated by sustainable and carbon-neutral energy sources.

When trying to position space energy systems in the proportional triangle in Fig. 1, these would be located in the extreme lower right corner. Due to the absence of hydrocarbons, and thus stored solar energy, only two energy sources are available in space: solar and nuclear. Therefore, taking the energy triangle of Fig. 1, space energy systems are not located where any future sustainable terrestrial system will need to be positioned but the conditions in space are even more stringent. Converted solar energy like hydroelectric, the largest contributor of renewable energy, biomass and wind power (except on some planetary surfaces) are not available in space. Only primary solar power in form of solar irradiation can be used together with the most concentrated form of energy available at the moment: nuclear power.

E.2.2 European Dimension

Looking at the more restricted European picture, the following main parameters are taken into account:

- Renewal of large fraction of power plants;
- Increasing energy import dependence;
- Required reduction of greenhouse gas emissions.

A significant portion of European power plants have been built 30 to 40 years ago and reach the end of their nominal lifetime. Against this background a number of European countries have recently started an energy debate on the choices of the future European energy mix.[5]

The International Energy Agency estimates the required investment into the construction of new power plants to substitute part of the ageing ones to be 531 B€ until 2020.[4]

The European Commission and many European countries are actively and substantially supporting the gradual increase of the total share of renewable energy sources.

The European Commission has set a very ambitious target of doubling the share of renewable energy consumption from the current 6% to 12% by the end of this decade. Excluding the probably constant share of hydropower (4%) this means a four-fold increase of the share of essentially wind, solar and biomass generated power.[6]

In addition, the overall energy import dependence of the (enlarged) European Union is expected to increase from the current 50% to 70%.[6] While growing import dependence is not necessarily a threat to security supply as such, it certainly will increase the interest for alternatives with the potential to alter this trend.

E.3 Objectives

While large-scale terrestrial or space solar power plants are not expected to play any significant role in the energy system within the next 20 years, the next large energy discussion after the current one is likely to take place around 2020/30.

Given the long technology maturation times as well as the long life-cycles of power plants and the intermediate nature of the concept: too advanced for mainstream programs but also too attractive as a long-term solution for a range of energy related problems to be neglected, one of the long-term objectives of the current SPS Programme Plan is to advance the concepts in order to reach a decision-enabling maturity level.

Having acknowledged the fact that there are no principal technical “show-stoppers”, that conceptual and technological progress has reduced the required orbital masses significantly and gradually over the last 30 years (and that there is little reason to believe that this trend is changing soon), the first objective was to assess the general viability of the concepts.

While such assessments have been undertaken in the past, none of them seems to have been able to convince a larger audience than the inner SPS research community. For the credibility and impact of the validation phase results, the studies were therefore lead by independent energy consultants.

E.3.1 Boundary Conditions

The general frame for the validation phase was fixed by:

- limitation to the wider European context;
- comparison with terrestrial solar power systems;
- assessment of energy payback times;
- comparison of technologies at same technology maturity levels;
- integration into realistic projections of European energy demand patterns in 2025/30.

The limitation to only European scenarios (with a wide interpretation of Europe) imposes some severe restrictions since most of the past SPS scenarios were designed to be inherently global. This restriction was important in order to include the concepts into a 2025/30 European electricity system with realistic demand profiles.

The restriction of the comparison to only solar power systems makes the comparison easier and fairer but also implies that very large scenarios are less realistic for the terrestrial option (e.g. solar power systems supplying more than 50% of the total European demand).

Given that one of the regular critics is related to alledged unreasonably high energy pay-back times (for terrestrial as much as for space systems), their thorough assessment was an integral part of the comparison. It is furthermore important to notice that the comparison was based on actual component material energy costs (contrary to the easier but less accurate cost-energy relationship).

E.3.2 Integration: space and terrestrial plants

Given the different levels of technology maturity for space and terrestrial solar power concepts and the high share of the storage costs for terrestrial base-load systems, the possible mutual advantages of an integration of space and terrestrial solar power plants were assessed.

E.4 European Approach — Methodology

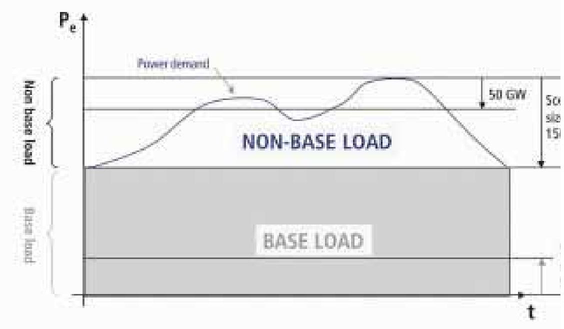


Figure E.4.1: Definition of base and peak-load (non-baseload) power as used for the present assessment.

E.4.1 European Network on Solar Power from Space

The first step was taken in August 2002 with the creation of the European Network on Solar Power from Space.[2,3] It provides a forum for all relevant and interested European players in the field of SPS, including industry, academia and institutions.

After the definition of the main aspects of the SPS Programme Plan with its three phases as described in [2], the activities were done in parallel ESA-internally within studies by the Advanced Concepts Team and by European industrial and academic contractors.[2,7,8,9,10]

E.4.2 Integration of Terrestrial Solar Power Expertise

Two parallel industrial studies were undertaken. The two consortia were led by independent energy consultant companies, which coordinated the space as well as terrestrial solar power expertise.

E.4.3 Power Consumption Profile

The scenarios were divided into the provision of base-load power and the provision of peak-load power. For this purpose, base-load power was defined as the constant provision of the lowest daily demand level. Peak load power was then defined as "non-base-load" power as shown in Figure E.4.1, which also gives the typical daily power lead profile for Europe.

E.4.4 Supply Scenarios

Solar power satellites are frequently proposed in the multi- GW region, while terrestrial plants are currently proposed in the several MW region. In order to derive the scaling factors for space and terrestrial solar power plants, different plant sizes ranging from 500MW$_e$ to 150GW$_e$ and 500GW$_e$ for the peak-load and base-load scenarios respectively have been analysed.

E.4.5 Launch Costs

Launch costs are the single most important parameter in assessing the economic viability of solar power satellites. The assumption of fixed launch costs would predetermine the outcome of system comparison studies.

As a consequence, launch costs were treated as open parameters for the present assessments between boundaries given by the current launch cost as upper and the fuel costs as lower limit.

In order to overcome the "chicken-egg" problem of: the launch frequency required by the construction of SPS reduces the launch costs to values required for the economic construction and operation of SPS, a "learning curve approach" was agreed upon by both consortia. Starting from current launch costs, a 20% reduction was assumed by each doubling of the total launch mass. (progress rate of 0.8)

In a first step, space and terrestrial plants were compared by excluding launch costs. This comparison and the total cost difference were then taken to determine the maximum allowed launch costs for the space scenario in order to be competitive with terrestrial plants.

In a third step, the progress rate was used to determine the reduction of the launch costs due to the launches of SPS components for all scenarios. This value was then compared to the required value to become competitive for a certain scenario as determined in step two. The approach did not take into account potential multiplication factors due to the opening of additional markets created by lower launch costs.

E.5 Reference Systems - Terrestrial

For the base-load power supply scenario, one consortium opted as most likely system for a system of multiple 220 MW$_e$ solar thermal tower units distributed within the south European sunbelt region (including Turkey). The other consortium based the analysis on a solar thermal trough system installed in an unpopulated area in Egypt. Both consortia considered PV plants as higher-cost alternatives with current technology but with large cost reduction potential for the 2020/30 timeframe.

The system of choice for the peak load power supply of one consortium was a highly distributed PV-based scenario, where the amount of unused, potentially available and usable building surfaces were taken into consideration. The other one opted for the same design as for the base-load solar power plant.

For a detailed description of the solar thermal and terrestrial PV technologies, it is referred to [11,12,13,14,15,16,17,18,19]

E.5.1 PV System Technology

The assumptions of for 2025/30 PV technology are a 20% PV module efficiency based on a 3rd generation multi-junction cell. The state of the art turn-key total investment costs are assumed at 4 500 €/kW$_p$ at a current total capacity of 2 GW$_p$. The cost calculations for the 2025/30 scenarios for terrestrial as well as for space based PV power plants were based on a 20% cost reduction by each production doubling (which corresponds to the trend of the last decade) until the total installed capacity reaches 500 GW$_p$ when the reduction per each doubling was assumed to be only 8%.

A total plant life-time of 25 years with operations and maintenance costs of about 2-3% were taken as basis.

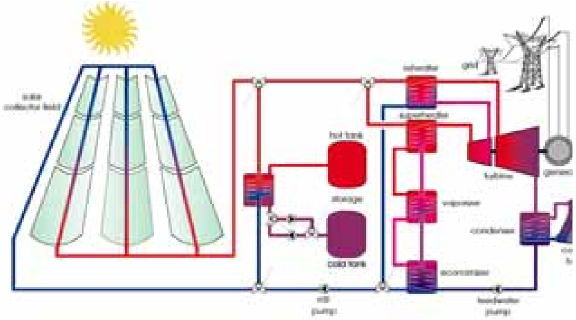


Figure E.5.1: Outline of a terrestrial solar trough plant

E.5.2 Solar Thermal Technology

Solar thermal technology for electric power plants is more mature than PV technology for power plants and under certain conditions already competitive to traditional fossil fuel based plants.[14,13] This is valid for solar thermal trough plants as well as for solar tower plants. The schematic layouts of a solar thermal trough and tower plants are shown in Figures E.5.1 and E.5.2.

A state-of-the-art cost of 225 €/m^2 of effective trough collector area have been assumed with additional 800 €/kW$_e$ for the power block and 30 €/kWh$_{th}$ for the thermal storage. For the 2025/30 scenario, a progress rate of 0.88 was assumed (12% decrease per each doubling of installed capacity), changing to 0.96 after installation of 500 million m^2 of effective collector area. (2004: about 2.3 million m^2)

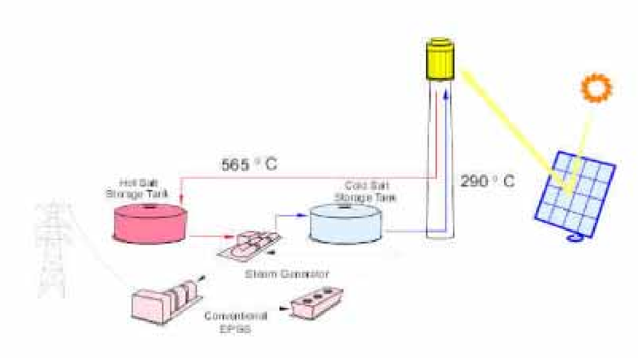


Figure E.5.2: Outline of a terrestrial solar tower plant

The baseline for solar thermal tower plants was an unit size of 220 MW$_e$ covering an area of 14 km^2 with a capacity factor of 73%. The current levelized electricity costs (LEC) of 0.042 €/kWh$_e$ are expected to fall to 0.03 €/kWh$_e$ by 2025/30.

E.5.3 Storage Systems

The Egypt based solar thermal trough plant concept relies on the availability of adapted local terrain features for the implementation of a pumped hydrostorage system.

The distributed solar thermal tower scenario uses local compressed hydrogen storage units as a baseline (pumped hydrostorage was considered as an alternative in case of appropriate local terrain).

State of the art pumped hydrostorage plants (1 GW, 6 GWh, discharge efficiency of 75%) present an investment cost of about 14 €/kWh + 700 €/kW that is assumed to decrease by 15% to approximately 12 €/kWh + 600 €/kW with operation costs of 4 €/MWh until 2025 (4 GW, 24 GWh, discharge efficiency of 85%).[20]

In case of the hydrogen storage system for 2025, investment costs of the electrolyzer are assumed to be 500 €/kW of power of produced hydrogen, corresponding operation and maintenance costs of 1.5% of the overall investment costs. For the pressure storage vessel 1.92 million € are estimated per each unit. Finally, for the re-conversion equipment, 500 €/kW$_e$ of investment costs and 0.01 € per produced kWh$_e$ are assumed.

E.5.4 Transmission Systems

The scenario based on a central large terrestrial solar trough plant in Egypt relies on relatively long power transmission lines. The chosen technology were high voltage direct current (HVDC) lines with a capacity of 5 GW$_e$ per line as of today and an expected increase to 6.5 GW$_e$ by 2025/30. This also reduces the total cost from today 60 M€/(1000 km · 1 GW) to 46 M€/(1000 km · 1 GW) with constant per-station costs for the required DC-AC converter stations of 350 M€ each. Operations and maintenance were taken into account at 1% of the total investment costs.

The scenario based on distributed solar tower plants across the European sunbelt does not require significant additional transmission capacity for scenarios up to 100 GW$_e$ above which the concepts rely on the HVDC current technology.

E.6 Reference Systems - Space

Given the restriction to European scenarios, only geostationary space systems were taken into account. While one consortium has opted for wireless power transmission by laser, the other preferred the 5.8 GHz microwave wavelength. Both concepts rely on land-based terrestrial receiver sites (instead of sea-based receivers).

In principal, the first phase was not intended to develop new space solar power station designs, but to rely on the most advanced technical concepts proposed. (European Sailtower concept, the concepts proposed during the NASA Fresh Look and follow-on studies as well as Japanese concepts)[21,22,23]

Due to limited data on concepts relying on laser power transmission, some further assumptions have been made. The general outline of the laser-based space plant is a geostationary space units with 111 km^2 of thin film PV cells augmented by concentrators of the same area. The 20% efficient system generates 53 GW$_e$ in orbit, feed into a 50% efficient IR-laser generation system at 1.06 µm transmitted with average losses of about 38% essentially due to beam shaping and atmospheric attenuation to an almost 70 km^2 large PV reception site in North Africa. The ground PV system would have a 20% efficiency for direct sunlight but a 52% conversion efficiency for the IR-laser beam. Adding additional 4% collection losses in space and 4% losses on ground, the space segment would deliver a constant supply of 7.9 GW$_e$ to the terrestrial power grid.

E.7 Comparison Results

E.7.1 Base-load Power Supply

In the case of base-load scenarios, terrestrial solar tower plants with local hydrogen storage capacities promise electricity generation costs between 9 €cent/kWh for the smallest (500 MW_e) and 7.6 €cent/kWh for the largest (500 GW_e) plants.

Under those conditions, solar power satellites would not be competitive with the smallest scenarios even at zero launch costs. For the 5 GW_e and larger scenarios, launch costs between 620 and 770 €/kg are required for SPS to be competitive with terrestrial plants. In case local pumped hydrostorage facilities are available, the required launch costs would be significantly lower, dropping to roughly one third of these values. (Table E.7.2)

For the comparison of laser-based space systems with terrestrial systems in North Africa the space and ground systems are more integrated and cannot be discussed and compared completely separately since the ground site is used at the same time as receiving site for the space system and as (independent) terrestrial solar power plant based on direct solar irradiation.

With 530 €/kg into LEO launch costs, base-load power supply scenarios by space-based systems for 10, 25, 50, 100 and 150 GW_e scenarios were compared with terrestrial-only concepts located in North-Africa. The total LEC for the space scenario range from 0.26 €/kWh for the smallest to 0.10 €/kWh for the 150 GW_e concept. The summary parameters of the system are listed in Table E.7.1.

For the combined system (the integration of space and terrestrial solar plants) the range of (terrestrial) technology options imposed the reduction of the analysis to distinctive scenarios. Within each scenario, the levelized electricity costs were calculated for the entire range: from power from space only to no additional power from space. The design of the ground receiver changes in type, spacing and inclination depending whether it should be optimized as ground system for the space segment or as pure terrestrial solar plant.

The four scenarios assessed in detail were

- central PV receiver optimized for laser beam, additional PV optimized for solar irradiation; pumped hydroelectric storage (Scenario S-1);
- central PV receiver optimized for laser beam, additional PV optimized for solar irradiation; hydrogen pressure vessel storage (Scenario S-2);
- entire PV receiver optimized for laser beam; pumped hydroelectric storage (Scenario S-3);
- entire PV receiver optimized for solar irradiation; pumped hydroelectric storage (Scenario S-4).

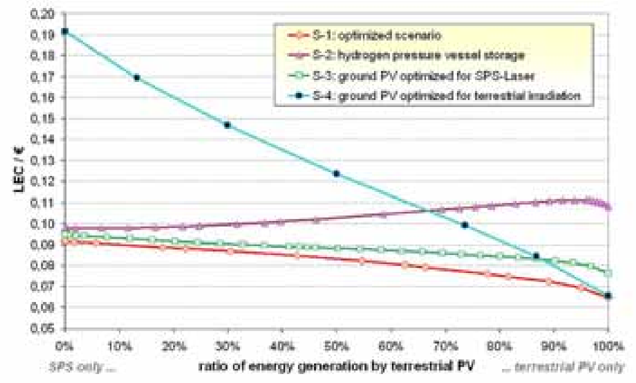


Figure E.7.1: Comparison of different scenario combinations of space and terrestrial solar power plants

The results of the combination in terms of levelized electricity generation costs for the entire range from all-space to no-space extremes for each of the four scenarios are displayed in Figure E.7.1. It can be seen that given the uncertainty inherent in 20-year forecasts, the LEC for the different scenarios (except the one optimized for converting only direct solar irradiation; S-1) are very close to each other and not changing dramatically by changing the percentage of space to ground supplies.

As general tendency, the importance influence of the availability of cheap local storage is confirmed by these curves: where (cheap) pumped hydroelectric storage is possible due to terrain specifics, terrestrial plants are generally producing cheaper electricity than space plants, even if the ground station is optimized for the space segment. This tendency has to be taken with some care however, since the reduction from an *all space* to an *all terrestrial* case is only about 1 €cent. The results are based on launch costs of 530 €/kg.

TABLE E.7.1 SPACE SYSTEM PARAMETERS - LASER POWER TRANSMISSION

Demand	GW	10	25	50	100
units (space/ground)		1/1	3/1	6/2	12/4
space PV cap.	GWp	22,1	66.4	133	266
terr. PV cap.	GWp	36653	36653	17	33.9
stor. cap.		200	500	1000	2000
LEC	€/kWh	0.26	0.166	0.137	0.113
EPT	Months	4.2	3.7	3.7	3.7

Over all ranges the most advantageous scenario is scenario S-1, with a terrestrial receiver containing a central part optimized for converting the laser from the SPS and the surrounding photovoltaics optimized for direct solar irradiation. In case pumped hydroelectric storage is available, the *all terrestrial* solution prevails over the all space solution by close to 3 €cent/kWh. In case hydrogen storage is required, the *all space* option is little more than 1 €cent/kWh cheaper than the *all terrestrial* scenario. Since both of these curves have their minimum on the (opposite) extremes, a combination of both will have a local minimum somewhere close to a scenario with 20% space and 80% terrestrial supply.

TABLE E.7.2 COMPARISON: BASE-LOAD SCENARIOS
SPACE (RF POWER TRANSMISSION)–TERRESTRIAL (SOLAR TOWER)
PUMPED HYDROGEN OPTION IN BRACKETS

Total Power Supply GWe	**Concept**	**electricity generation cost** €/kWh	**permitted launch costs** €/kg (LEO)
0.5	terrestrial	0.090 (0.059)	
	Space	0.280 (0.280)	-
5	terrestrial	0.082 (0.053)	
	Space	0.044 (0.044)	750 (200)
10	terrestrial	0.080 (0.051)	
	Space	0.047 (0.046)	620 (90)
50	terrestrial	0.076 (0.049)	
	Space	0.035 (0.034)	770 (270)
100	terrestrial	0.075 (0.047)	
	Space	0.034 (0.033)	770 (250)
500	terrestrial	0.076 (0.050)	
	Space	0.039 (0.039)	670 (210)

TABLE E.7.3
COMPARISON: PEAK-LOAD SCENARIOS
SPACE (RF POWER TRANSMISSION)–TERRESTRIAL (SOLAR TOWER)
PUMPED HYDROGEN OPTION IN BRACKETS

Total power supplied GWe	Concept	Generation cost €/kWh	Required launch cost (€/kg)
0.5	terrestrial	10.6 (10.2)	
	space	441	-
5	terrestrial	7.6 (6.6)	
	space	36	-
10	terrestrial	5.3 (4.0)	
	space	19	-
50	terrestrial	1.09 (0.7)	
	space	0.871	155 (-)
100	terrestrial	0.673 (0.48)	
	space	0.246 (0.245)	958 (540)
150	terrestrial	0.532 (0.280)	
	space	0.131 (0.130)	1615 (605)

With lower launch costs, this local minimum will shift towards the right side of Figure E.7.1, the *all terrestrial* option and inversely will tend towards a higher percentage of the overall power delivered from space (left side of x-axis).

E.7.2 Non base-load Power Supply

For non-base-load scenarios, solar tower plants with local hydrogen storage capacities have generation costs between 10 €/kWh for the smallest scenarios to 53 €cent/kWh for the largest (150 GW_e) plants. Solar power satellites reach potentially competitive electricity generation costs only above relatively large plant sizes of about 50 GW_e.

For the 50 GW_e and higher scenarios, launch costs between 155 and 1615 €/kg would be required for SPS to reach a competitive level to terrestrial plants. In case local pumped hydrostorage facilities are available, the required launch costs would be lowered by about a factor two. (Table E.7.3)

E.7.3 Energy payback times - primary validity

Space as well as terrestrial solar power plant concepts have been “accused” of violating the fundamental law of every power plant: generating more energy than necessary for their proper construction. It was therefore important to assess the exact cumulated energy demand (CED) of the systems and compare it with the energy output over their lifetime. The resulting energy payback time provides a measure for the validity of the concepts as power plants.

There are several methods to assess the cumulated energy demand of any system. The fasted but also most imprecise method is an energetical input/output analysis. This method was already partially applied to SPS systems in the past, in part based on energy estimates derived from material costs, assuming a reliable €-Joule relationship. In case all the components are known a material balance analysis can be made, combining the mass of all single components with its specific energy demands obtained from specialized databases.

TABLE E.7.4
COMPARISON: ENERGY PAYBACK TIMES

Total Power Supply GWe	Concept	energy payback time Months
0.5	SOT1 (H2)	8.4
	SOT2 (pumped)	7.7
	PV (pumped)	8.2
	SPS laser	-
	SPS μ-wave	24
5	SOT1 (H2)	8.4
	SOT2 (pumped)	8.3
	PV (pumped)	9.2
	SPS laser	-
	SPS μ-wave	4.8
10	SOT1 (H2)	8.4
	SOT2 (pumped)	8.9
	PV (pumped)	8.2
	SPS laser	4.4
	SPS μ-wave	4.8
100	SOT1 (H2)	8.4
	SOT2 (pumped)	8.1
	PV (pumped)	8.3
	SPS laser	3.9
	SPS μ-wave	4.8
150	SOT1 (H2)	8.4
	SOT2 (pumped)	8.2
	PV (pumped)	8.5
	SPS laser	-
	SPS μ-wave	4.8

SOT1: South European Solar Tower case
SOT2: North African Solar Trough case
PV: North African Solar Photovoltaic case

The present analysis relies on a complete material flow analysis, the most precise method to determine the CED. For some parts of the space system for which the data for the exact material flow analysis were not available, the method of material balance was used, partially based on CEDs provided by specialized databases. (Table E.7.4)

In all considered cases, the energy payback times for space and terrestrial solar power plants were lower or equal to one year. For the Egypt-based terrestrial system, the energy payback times seem to be slightly higher than for the distributed system in the European solar belt. In both cases, from a purely energetic point, solar power satellites promise a slightly shorter energy payback time, ranging depending on the size and the concept (all including the launchers) from 4 month to 2 years.

It should be noted that while using slightly different methods and different space concepts, the assessments for the space segments derive almost exactly the same values (3.9 to 4.8 months) despite their different transmission technologies. The terrestrial scenario based on solar thermal tower plants (local hydrogen storage) in south Europe leads to energy payback times of 8.4 months, the solar thermal trough case (with pumped hydroelectric storage) in North Africa has a calculated payback time of 8.1 to 8.9 months. The energy payback times for the terrestrial photovoltaic case in north Africa are expected to fall from about 31 months with advanced current technology to 8.3 months based on 2030 PV technology.

The detailed assessments have shown that both, space and terrestrial solar plants have extremely short energy payback times and are from a purely energetic point of view attractive power generators.

E.8 Conclusions

In an attempt to contribute to the discussion on the most appropriate options for a sustainable energy system for the 21st century, solar power from space concepts were compared with terrestrial solar power plants in the timeframe until 2030 on equal technology assumptions.

While terrestrial solar power plants are expected to contribute significantly to the European electricity production in the next 20 years, solar power satellites are expected to reach their technical and economic maturation phase only at the end of the considered timeframe.

The competitiveness of the space option increases with increasing total plant sizes. Under the given assumptions, space options are competitive with terrestrial plants only for relatively large solar power plants (depending on the type from 0.5 to 50GW$_e$).

Earth-to-orbit transportation is the single most important factor requiring a decrease of more than one order of magnitude compared to current launch costs. Depending on the plant size, launch costs between 155 and 1615 €/kg$_{LEO}$ for peak-load and around 600-700 €/kg$_{LEO}$ for base-load supply scenarios are necessary to be competitive with terrestrial solar power plants.

The advantage of combined space and terrestrial solar plants based on laser power transmission depends on the available terrestrial storage facilities, especially appropriate terrain for large pumped hydroelectric storage.

Both, space and large terrestrial solar power plants have very attractive, low energy payback times. Almost all space and terrestrial concepts produce within less than one year more energy than was needed to produce and operate them, based on a detailed complete material flow analysis.

Based on the obtained results, solar power from space confirms its potential as attractive option for a sustainable energy system, requiring significant technology maturation and further investigations into the most likely first steps, their integration into then existing terrestrial solar power plants.

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