# Solar Power Transmission: From Space to Earth

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*Abstract:* **With the introduction of restructuring in the electric power industry, the price and availability of electricity has become a primary issue for participating entities. This paper emphasizes the possibility of generating electricity in space by using solar cells in geo-synchronous satellites and utilizing wireless power transmission. The paper further discusses various techniques for utilizing the space power and emphasizes the possibility of transferring space power to earth in the form of microwaves using antennas called *Rectenna.***

*Keywords:* ***solar power, solar power satellite, microwaves, rectenna, wireless power transmission***

## INTRODUCTION

The concept of solar power satellites for generating electricity in space was first proposed by Peter Glaser in 1968 [1]. The power generated in space can be transmitted to earth as microwave signals which can be collected with the help of an antenna called Rectenna and then converted into electric power. Individuals have discussed the use of space solar power systems (SPS) as a prominent means of supplying energy to the earth to replace and conserve non-renewable sources of energy. The significance of greenhouse effect resulting from burning fossil fuels and escalating prices of fossil fuels have again brought to the public's attention the possibility of utilizing renewable energy sources. The time is certainly appropriate to reexamine the SPS project for making use of the abandon solar energy for generating electricity.

The International Energy Outlook 2004 (IEO2004) has projected a strong growth for worldwide energy consumption over the 24-year period from 2001 to 2025. The total world consumption of energy is expected to grow by 54 percent, from 404 quadrillion British thermal units (Btu) in 2001 to 623 quadrillion Btu in 2025. It is possible, however, that as environmental management programs or government policies—particularly those that are designed to limit or reduce greenhouse gas emissions—such as the Kyoto Protocol are implemented, the outlook for energy utilization would change and non-fossil fuels (including nuclear power and renewable energy sources such as solar, hydroelectricity, geothermal, biomass, and wind power) become more attractive. As the level of energy consumption is mounting throughout the world, the chances for the generation of uninterrupted renewable power is becoming more likely with the implementation of solar power systems.

The major drawback of terrestrial solar power generation is that power can only be generated during daytime hours, hence limiting the generation to almost 50%. Ground-based solar power is viable due to a fortuitous match between daytime peak for power consumption and solar power production. The main advantage of investing in SPS panels is the availability of sunlight in space throughout day and night.

## CONCEPTUAL DESIGN OF SPS

The National Research Council (NRC) study groups singled out the following technological advances relevant to SPS: improvements have been observed in the efficiency of solar cells and the production of lightweight solar-cell panels; wireless power transmission tests are progressing specifically in Japan and Canada; Robotics, viewed as essential to solar power satellite on-orbit assembly, has shown substantial improvements in manipulators, machine vision systems, hand-eye coordination, task planning, and reasoning; and advanced composites are in wider use and digital control systems are now the state of the art-both developments essential to building and utilizing solar power systems.

An 1100km altitude equatorial orbit is used for launching SPS as this choice minimizes the transportation cost and the distance for space power transmission. Various parameters are analyzed for certain altitudes and Fig. 1 shows the duration for power reception from various orbital altitudes by a rectenna located on the equator [2].

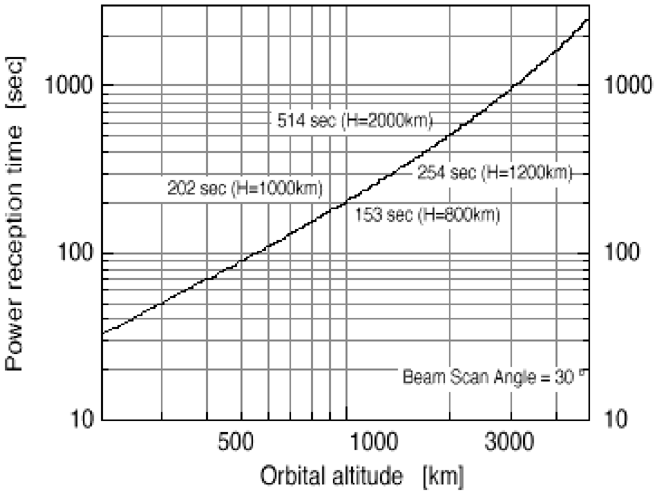

Fig. 1: Orbital altitude vs. reception time for a rectenna on the equator

A 2.45 GHz microwave frequency is used to transmit power from satellite to rectenna. The amount of power is defined by the microwave power originated from the satellite and not by the power received on earth. Fig. 2 shows a schematic of microwaves beam control and rectenna location [2]. The components of SPS are given as follows:

**Satellite:** Fig. 3 gives a general view of the satellite system. The satellite looks like a saddle back roof in which the roof is made of solar panels and the spacetenna (space antenna) is built on the bottom plane to transmit microwaves to the ground [2].

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Elements of the satellite system include:

- Buses
- Structure and Assembly
- Power Generation and Power Lines
- Spacetenna (transmitting antenna)
- Robotics

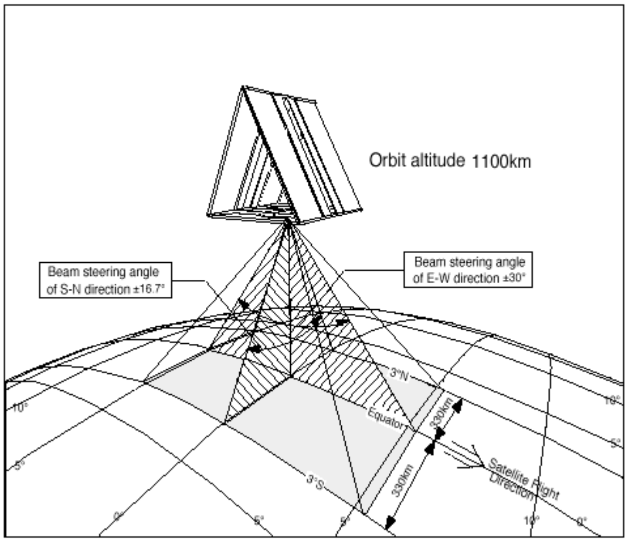

Fig. 2: Microwave beam scanning control

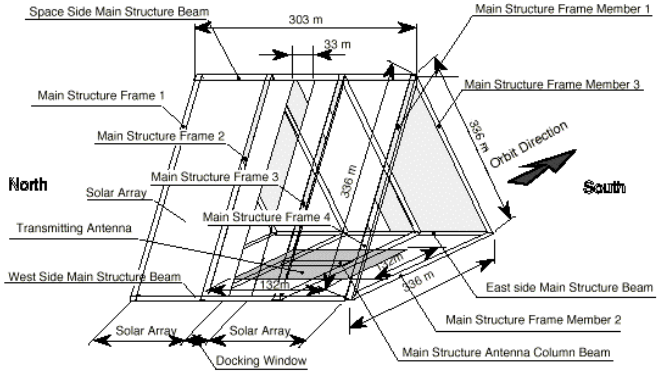

Fig. 3: Satellite system

## Power Generation and Power Lines:

**Solar Cell Array**: The following baseline data is based on the current performance of a ground-use silicon solar cell.

| | |
|---|---|
| Conversion Efficiency | 15% |
| Unit Weight | 0.22kg/m2 |
| Specific Power | 950W/kg |
| Thickness | 0.2 mm |

A subarray is composed of 12 solar cell units as shown in Fig. 4. The array module, composed of 110 subarrays, is a mechanical element for assembly. Each array module generates 180A at 1kV and weighs 270 kg. Forty-five array modules are assembled in each wing of the satellite including northeast, southeast, northwest, and southwest wings [2].

**Power Collection and Distribution**: The Wing Summing Bus Line (321 in Fig. 4) collects the electric power from the array modules. The bus lines are insulated copper plates 1 mm thick. They get wider as they approach the center of the solar power satellite to keep the joule loss per surface area constant. The Wing Summing Bus Lines are connected to the Central Bus Lines which are interfaced with the spacetenna system. The Central Bus Lines are insulated copper plates 0.7 mm thick by 100 mm wide. The power loss in the bus lines is 7 % in total. The total weight of the power lines is approximately 11,000 kg.

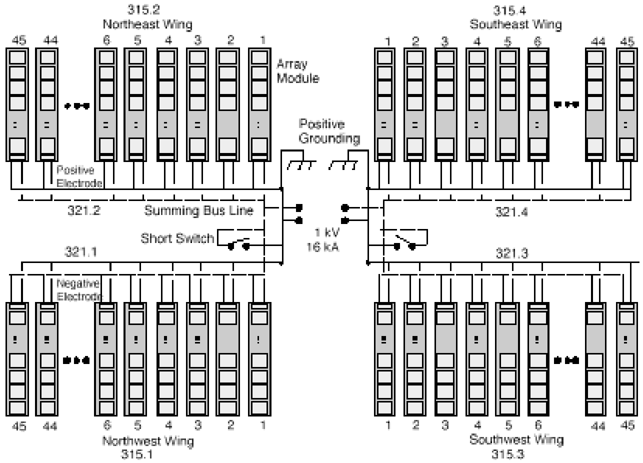

Fig. 4: Diagram of the entire power generation system

**Power Generation**: Power generation on SPS changes with the local time, depending on the sun angle on the arrays and the cell temperature. The diurnal and seasonal variation of the generation power have been calculated.

## Spacetenna Characteristics:

### Electrical Characteristics

| | |
|---|---|
| Frequency | 2.45 GHz |
| Beam control | Retrodirective |
| Beam scanning angle | +30 deg (east-west)<br>+16.7 deg (north-south) |
| Power distribution | Constant |
| Power Density | 574W/m2 |
| Max Power Density on ground | 0.9W/cm2 |
| Input power to spacetenna | 16MW |
| Transmitting power | 10MW |

### Mechanical Characteristics

| | |
|---|---|
| Shape and dimension | 132m x 132 m square |
| Mass | 134.4 ton |
| Number of array modules | 88 |
| Number of subarrays | 1936 |
| Number of antenna elements | 2,547,776 units |
| Number of pilot receivers | 7,744 units |

## WIRELESS POWER TRANSMISSION

Wireless power transmission is made possible by three ways:

- Microwave based wireless power transmission system
- Laser based wireless power transmission system
- Hybrid laser-microwave wireless power transmission system.

**Microwaves:** Microwave signals play a significant role in space exploration and technology [2]. Microwave wavelengths are in the range of 0.3cm - 30cm. Microwave signals are good for transmitting information from one place to another because microwave energy can penetrate haze, light rain and snow, clouds, and smoke. Longer microwaves that are closer to a foot in wavelength are used to heat food in a microwave oven. Shorter microwaves are used in remote sensing. These microwave signals are used in radar devices like the Doppler radar for weather forecasts. Microwaves used for radar are just a few inches long.

There is almost nothing in outer space to block or absorb lower frequency waves such as radio waves. However, the earth's ionized upper atmospheric layer—the ionosphere—reflects or absorbs lower frequency waves before they leave the vicinity of the earth. However, microwaves are different; they can penetrate the ionosphere and travel all the way to Mars which makes them useful for exploring the universe. Like light, microwaves travel very fast, about 186,000 miles (300,000km) per second in air. In addition, both light and microwaves get weaker the further they travel from their source, and both can be focused into narrow beams by lenses or concave mirrors called reflectors. Microwaves can be focused in dish-shaped reflectors

**Laser Wireless Power Transmission:** Satellite and system architectures based on laser wireless power transmission was first considered seriously during the SPS Exploratory Research and Technology (SERT) program [4]. Laser systems have one major advantage for power transmission which is the aperture collection efficiency. Whereas microwave power transmitting and receiving antennas are sized in kilometers, laser systems can be sized in meters. A secondary advantage is that laser based systems lend themselves more readily to incremental developments than microwave based systems. However, the major hurdle that lasers based systems face is atmospheric losses especially due to the rain attenuation. To provide continuous power, which would be necessary to qualify SPS as base load power generation, the laser system would either have to have massive ground energy storage capability or multiple sites located sufficiently far apart such that one of the sites would be available at all times.

With the lower delivered power per site design criteria of the current studies compared to the DOE/NASA reference system, beam safety has minimal influence on the design of a microwave based solar power satellite system, however, it has been a major factor for laser based systems. To deal with laser eye and skin exposure limits, a system of geostationary cluster of laser satellites are distributed uniformly through a sufficient solid angle of space, with the beams from the satellites spread uniformly over the 600m diameter photovoltaic array-receiving site. With such a system, it is possible to maintain safety standards and still deliver IR light (1.03µm, 1.06µm) with a seven-fold increase in power density over natural sunlight. Practical realization of such a system is through a HALO orbit in which the satellites appear to move in a circular orbit about a fixed point in space. Individual satellites would have multiple solid-state lasers powered by photovoltaic arrays.

Lasers are dispersed among photovoltaic cells to minimize power management. Light is beamed directly to the earth or collected by mirrors or through fiber optics to a central steering mirror and then beamed to the earth. A novel approach to overcoming weather interruption of laser based power beaming is to use the beamed power to store energy at the receiving site for later transportation. A low-earth-orbit (LEO) satellite would use a concentrator fed solar. Integrated Symmetric Concentrator with concentrator mirrors, photovoltaic arrays and microwave transmitter disc (500m in diameter) pumped laser to deliver 10MW of laser energy focused into a tank of seawater containing titanium dioxide as a catalyst to split the water into its component hydrogen and oxygen. Hydrogen can be used as fuel or it can be reacted with CO2 to make methane.

**Hybrid Laser-Microwave Wireless Power Transmission*:*** Laser and microwave wireless power transmission each have unique advantages, i.e., lasers require smaller apertures and microwaves are nearly immune to rain and other atmospheric conditions. Proposals are made to combine the two options such that each would operate in its most advantageous environment. The key to the design proposal is a platform operating in the stratosphere at about 20km height. Lasers can be used to beam power from satellites at geostationary orbit through space (no atmospheric attenuation) to a photovoltaic array on the platform. The power would then be retransmitted with microwaves from the platform to a ground rectenna. This would minimize both the size of the satellite transmitter and ground receiver for an all-weather transmission system. Drawbacks to such a system include efficiency losses due to the conversion/retransmission step and the likelihood of exceeding microwave beam power density safety standards. Fig. 5 depicts the schematic of SPS.

Fig. 5: Schematic of SPS

## RECTENNA FOR ELECTRICITY SUPPLY

The ground segment of the power system is rectenna. A typical rectenna is shown in Fig. 6 [2]. Rectenna receives the transmitted power and converts the microwave power to direct current (dc) power. Rectenna is an antenna comprising a mesh of dipoles and diodes for absorbing microwave energy from a transmitter and converting it into electric power. In future Rectenna can be used to generate large-scale power from microwave beams delivered from orbiting SPS satellites.

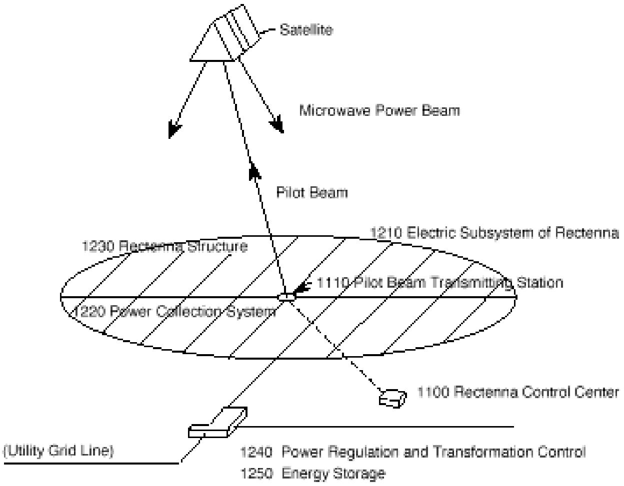

Fig. 6: Diagram of rectenna

The rectenna system may be developed for different purposes such as a small-scale low-cost system, a full-size maximum-output system, and a system intended to be developed later into a commercial system. At least one SPS rectenna site will be used as an SPS operation research center. Rectennas may deliver power into an existing grid or operate independently.

For power systems applications, two types of rectenna designs have been considered to date, i.e., high-efficiency wire mesh reflector supported on a rigid frame above the ground, and the low-cost magic carpet which could be pegged to the ground. Power collection, conditioning, and energy storage will be provided according to customer requirements. To deliver power for the maximum length of time, rectennas will be at least 1200km apart. Rectenna construction and operation will have environmental and economic impacts which will need to be analyzed for each site. Fig. 7 shows equatorial zones where electricity of SPS can be received [2].

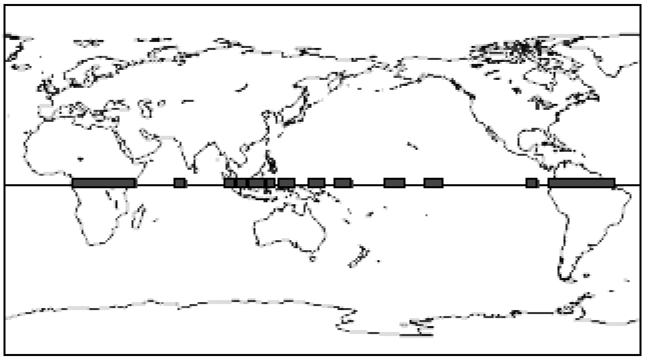

Fig. 7: Equatorial zones serviceable by SPS

The feed and rectifier microwave circuitry will be placed below the ground plane which makes it possible to isolate the rectifier circuitry from direct exposure to the incident microwave energy and thus prevent spurious coupling of microwave energy onto dc conductors. Yet another advantage of mounting the rectifier circuitry below the ground plane is that the ground plane serves as an effective thermal sink for diodes. The ground plane is not a single conductive plane but, rather, an array of dc-isolated capacitive-coupled islands registered with overlying antenna patches. A thin layer of copper-coated polyimide affects the capacitive coupling. The dc isolation of ground-plane islands in conjunction with the orthogonality of the layout makes it possible to use these islands as parts of the series-connected dc output circuitry.

Preliminary experiments have demonstrated that a rectenna of suitable design can be used to operate in an inverse mode in which radio frequency (RF) power is generated in the rectenna rectifier circuits and radiated by the rectenna antenna elements. This experimental finding provides encouragement for the use of rectennas as bidirectional (both transmitting and receiving) devices in developmental microwave wireless-power-transmission systems. Heretofore, a bidirectional microwave terminal for a typical conceptual wireless-power-transmission system might have included (a) a transmitter comprising a transmitting antenna connected to an oscillator, (b) a receiver comprising a separate rectenna. If only one device — a rectenna capable of operating in transmitting as well as receiving mode — could be used at each end of a microwave power link, then the cost of the link could be reduced. Potential applications for inverse rectennas lie in the microwave wireless transmission of power between any two of the following: ground stations, airships, aircraft, and spacecraft.

## TRANSIENTS TO BE CONSIDERED

There are ranges of transient conditions [5] which rectenna will experience and, in order for SPS to be useful to utilities, they will need to be managed while continuing to deliver power predictably:

**Start-up and Shut-down Transients:** For minimizing the transients, it is possible to start the SPS power delivery in various ways: Low power delivery centered on rectenna while building it up gradually to its maximum; full power beam centered on rectenna which is initially unphased and becomes progressively narrower while aimed at rectenna; sequential switching-on of different segments of transmitting antenna while aimed at rectenna and switching-on other segments to deliver full-power while phasing the beam onto rectenna. The behavior of rectenna and its subsystems will needed to be analyzed in each case in order to select the optimum mode of operation and to detect any system malfunctions.

**Change-of-Load Transients:** During electric power system operations, change of load transients could affect the operation of rectenna. It is possible to monitor the rectenna during power reception when the load to which it is delivering power is changed. Rectenna could operate stably during load transients through switching in and out different segments of rectenna and through altering the load being drawn through the power conditioning system.

**Load Following:** A particular case of change-of-load transients will be when SPS is used for load-following. The potential value of the satellite system would be considerably increased if rectenna could be used efficiently for load-following. In general, reducing the power drawn from a rectenna requires either the power output of satellite's solar arrays to be reduced or for power to be dumped somewhere else in the system, such as an increase in power reradiated from the rectenna. The latter would be more or less acceptable depending on its characteristics.

**Fault Transients:** Another type of transient through which rectennas must operate stably is the range of component failures for which they will be liable. In order to reach a targeted level of overall reliability, a commercial rectenna can be designed with components of specified degrees of reliability which can be maintained properly to achieve the targeted reliability.

**Eclipse Transients:** A geo-stationary SPS would on occasion pass through the earth's shadow and lose all or part of its power output. This can be planned in advance.

## PRELIMINARY SOLAR POWER SATELLITE

Spurred on by the oil crises of the 1970's, the US Department of Energy and NASA jointly studied the preliminary version of SPS during that decade. The result of the study was a SPS design with a 5 x 10 km rectangular solar collector and a 1km in diameter circular transmitting antenna array. The solar power satellite would weigh 30,000 to 50,000 tons. The power would be beamed to the earth in the form of microwave signal at a frequency of 2.45 GHz which can pass unimpeded through clouds and rain. This frequency was set aside for industrial, scientific, and medical use, and is the same frequency that is used in microwave ovens. Equipment for generating the microwave signal was inexpensive and readily available, though higher frequencies was also proposed. The rectenna array would be an ellipse 10 x 13 km in size which could light through so that crops, or even solar panels, could be placed below it [8].

The amount of power available to consumers from such a satellite would be 5 billion watts (A typical conventional power plant supplies 500 million to 1 billion watts). The peak intensity of the microwave beam would be 23M watts per square centimeter. The reason that the satellite would be so large had to do with the physics of power beaming. The angle of divergence of the transmitted beam would be larger for smaller transmitter arrays. A highly divergent beam would spread out over a great deal of land area and might be too weak to activate the rectenna. In order to obtain a sufficiently concentrated beam, a great deal of power would have to be collected and fed into a large transmitter array.

Massive structures such as this would have been a significant engineering challenge. Because of their size, the satellites would have to be constructed in space. The plan envisioned sending small segments of satellites into space using the Space Shuttle. The materials would be stored at workstations in low earth orbit and towed to the assembly point by a purpose-built space tug. When the NASA-DOE [6] report was completed, the estimated cost for building a prototype was $74 billion. The construction of SPS would have taken about 30 years to complete. At the time, the United States did not appropriate funds to begin construction. Japan is currently exploring the concept of SPS. The goal of the program is to conduct preliminary strategic technology research and development to enable large, multi-megawatt to gigawatt-class space solar power system and wireless power transmission (WPT) for government missions and commercial markets.

The National Space Development Agency of Japan (NASDA) has plans to develop a satellite-based SPS. The concept is for a large satellite carrying solar panels placed in orbit at an altitude of 36,000km. Electricity generated by the satellite will be transmitted in the form of a laser to an airship floating in a lower orbit at 20km above the earth, and then to ground-based antennas as microwave signal or via optical fibers. The plan still has to deal with many challenges such as launch costs for solar panel construction and technical studies of laser transmission. The project team currently expects to complete basic laser technologies within the next 10 years and has set a goal to conduct its first power transmission test in 2025. More recently, a different approach has been proposed to use smaller low-orbiting satellites for transmitting to power smaller stations scattered around the earth's surface. Some physicists have suggested that existing communications satellites can be used for sending energy to the earth.

In recent years, there has been a renewed interest in SPS, due to concerns about a possible global warming resulting from carbon dioxide emissions of fossil fuel combustion. A study commissioned by the Space Studies Institute (SSI) [7] has shown that about 98% of the mass of the solar power satellite may be based on materials mined from the moon. A lunar infrastructure would have to exist for making this idea to happen. Recent works has shown that a solar power satellite can be built using thin-film solar cells deposited on lightweight substrates. Such an SPS could deliver perhaps ten times as much power per unit mass as proposed designs. The combination of lightweight materials, inexpensive launch systems, and a space infrastructure can make SPS a reality. For best efficiency the satellite antenna must be between 1 and 1.5km in diameter and the ground rectenna around 14 x 10 km. For the desired microwave intensity this design allows a transfer of 5,000 - 10,000 MW of power. To be cost effective it needs to operate at maximum capacity. To collect and convert that much power the satellite needs 50 - 150 square kilometers of collector area thus leading to huge satellites.

## LARGE-SCALE SPACE INFRASTRUCTURE

Development of SPS will require a large infrastructure for space transportation and space construction. This will present a large risk element unless the transportation infrastructure is developed and tested well before commitment to a SPS design. The transportation requirements will be orders of magnitude more than needed for the existing commercial applications such as communications satellites. A significant boost will be the identification of near-term, large-scale commercial applications of space missions. Pending such an as-yet unknown commercial application, the SPS infrastructure is dependent on the development of space infrastructure by space-exploration missions. Various unmanned missions, such as planetary probes (e.g. Cassini) and exploratory missions to the smaller bodies of the solar system such as asteroids and comets contribute little to the transportation infrastructure needed, although they are important preliminary elements to the long term exploitation of space resources.

An aggressive planetary exploration policy has additional long-term applications to SPS. The projected cost of a SPS could be considerably reduced if extraterrestrial resources are employed in the construction. One often-discussed road to lunar resource utilization is to start with the mining and refining of lunar oxygen, the most abundant element in the moon's crust, for use as rocket fuel to support the lunar base as well as exploration missions. Once the mining and refining process is in place to produce oxygen, the next-most abundant elements, aluminum and silicon, can be refined to produce solar arrays. Such lunar-manufactured solar arrays could have many applications in LEO, GEO, support planetary missions as well as and serve as primary power supplies for SPS. Thus, with the development of the component parts of a mature photovoltaic technology, beamed power for in-space use, and a space infrastructure, the implementation of a solar power satellite may consist only of integrating the pieces.

## PROBLEMS TO BE ENCOUNTERED

The problem is that possible risks for such a large project are very large and there is an understandable reluctance to committing enormous amounts of financial resources to a project with uncertain payoffs. The payoff time is long and fear of technological obsolescence is high. Electricity demand may be inaccurately forecast, and lower-cost generating technologies may alternatively be developed during the time required to develop and construct SPS. SPS must overcome the negative experiences with large projects of the nuclear power industry which invested heavily on long-term, large capacity projects and discovered that projected use did not materialize while costs and environmental objections ballooned.

A September 2001 review of NASA research on SPS by NRC found the research worthwhile although it noted that the funding levels for this project would have to be much higher to achieve its goals. The review noted that dramatic reductions would be needed in the cost of placing the SPS into the earth's orbit and in the cost of solar panels, and that significant progress is still needed in the technology to produce power in space and beam it back to earth. A progress report is given in Table 1.

## CONCLUSIONS

In a geo-synchronous system, SPS can be illuminated for over 99% of the time. The solar power satellite would be in the earth's shadow for only a few days at the spring and fall equinoxes and even then for a maximum of an hour and a half late at night when power demands are at their lowest. As there are many storage systems like compressed air energy storage and battery storage available, the energy from SPS can be stored during low peak times and used efficiently during the peak load periods. Despite that the concept of SPS was proposed nearly 30 years ago, no one has yet demonstrated its practical application. Since SPS was proposed, hundreds of billions of dollars have been spent on space activities, and hundreds of billions of dollars have been spent on nuclear energy research and development and manufacturing. But apart from $20 million spent during the 1970s in the USA, the total spending on SPS work throughout the world has been no more than a few $ million at most - and it is almost zero at present. This does not reflect its potential, it does not reflect a rational balance of its potential relative to nuclear energy, and it does not reflect the preferences of the public for renewable and pollution free energy production and delivery.

Table 1: Progress Report on SPS Project

| Description | Tasks Accomplished | To be accomplished |
|---|---|---|
| General configuration | Altitude dynamics<br>Basic structure production | Altitude stability<br>Tests in orbit |
| Assembly work and operation | Ground experiments with industrial robots | In-orbit work analysis<br>Space robot production |
| Solar array | Test of ground use solar cell Light weight | Mass production High temperature characteristics |
| Transmitting antenna | Light weight | Low cost High efficiency thermal design |
| Power transmit-receive system | System study | Ground to ground power transmission<br>Electrical performance evaluation |
| Test method | Model construction | Structure design verification test<br>Construction method verification test<br>Space environment simulation test |

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