Space-Based Solar Power Generation & Distributed Network

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ABSTRACT

Space-based solar power (SSP) generation is being a solution to our ever-increasing energy consumption and dependence on fossil fuels. Geosynchronous satellites are used for collecting sunlight, harnessing it to produce solar power and transmitting the generated power back to Earth using Wireless power transmission, safely and reliably through photovoltaic cells and transmit that power to ground based stations. Solar cells in orbit are not hindered by weather, clouds, or night. The energy generated by this process is clean and pollution-free. A distributed array of small satellites to collect power from the Sun, as compared to the more traditional SSP design that consists of one monolithic satellite. A high frequency beam will be used to aggregate collected power into a series of transmission antennas, which beam the energy to Earth's surface at a lower frequency.

This paper will give an overall view of the different SPS overall architectures and power transmission from space to earth, beaming satellite design, power beaming between satellites, high voltage techniques and frequency. The advantage of placing solar cells in space is the 24-hour availability of sunlight. The results highlight the effectiveness of this system as an environment friendly, low-loss and large-scale method of energy transfer.

Keywords: - Architectures, Distributed Network, Fossil Fuels, Monolithic Satellite, Photovoltaic Cells.

1. INTRODUCTION

Space based solar power station (SPS) is a notion in which solar power station revolves along the earth in the geosynchronous orbit. The respective energy is transmitted to earth's surface by using earth pointed wireless power transmitter (WPT) technology Fig.1 The average power per unit is 5-10 times more than on the ground. In the last few years, however, scientists around the globe and several researchers at the Energy Departments. [1][2]

IJARSE
ISSN 2319 - 8354

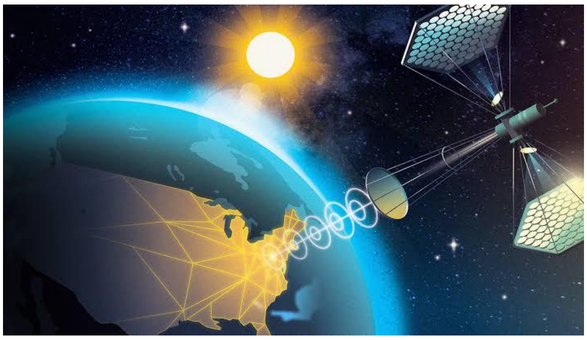

Fig.1 Space-Based Solar Power

Space solar power (SSP) was first introduced during late 1960s. However, low solar cell efficiency technology during the period which requires extremely large arrays (in terms of kilometers span) rendered its implementation impossible. Recently, both environmental and energy security issues have attracted policy makers to consider SSP, a renewable energy resource. Several countries such as China, India and Japan have shown considerable interest in developing SSP technologies. Japan Aerospace Exploration Agency (JAXA) plans to launch an experimental SSP satellite to space within the next few years and develop the first SSP satellite by 2030s. [3][4]

On earth, solar power is reduced by night, cloud cover, atmosphere, and seasonality. Some 30 percent of all incoming solar radiation never makes it to ground level Fig.2 In space the sun is always shining, the tilt of the Earth does not prevent the collection of power and there is no atmosphere to reduce the intensity of the sun's rays. This makes putting solar panels into space a tempting possibility. Additionally, SBSP can be used to get reliable and clean energy to people in remote communities around the world, without relying on the traditional grid to a large local power plant. [5]

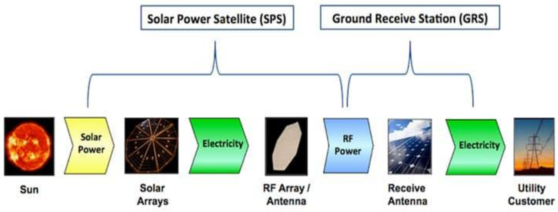

Fig.2 Functional elements of SBSP

2. SPS ARCHITECTURE & POWER TRANSMISSION

Satellite is defined as an object which revolves around the earth therefore, moon is also known a satellite and it is called as a natural satellite. On the other hand, human made satellites are called artificial satellites it is classified into four types [6]

1. Low Earth orbit (180-2000 km)
2. Medium Earth orbit (2000-35785 km)
3. Geosynchronous orbit (35786 km)
4. High Earth orbit (> 35786 km)

Solar energy because satellite receive 96% of light beams from sun which has maximum efficiency compare to other orbits. And whereas 4% losses due to equinox period earth pass through shadow [6]

Three types of SPS Architecture [4] have been classified as:

2.1 Type-I

2.2 Type-II

2.3 Type-III

2.1 Type-I:

SPS type-I comprises of sun pointing solar system module, earth pointing wireless power transmission (WPT) Fig.3 The microwave frequency for the SPS is taken to be in the range of 1–6 GHz, by compromising between the antenna size and atmospheric attenuation. This design has one major issue "high voltage power management and distribution system," which has been resolved in the following different types of designs [2].

Fig.3 Type-1 "Microwave" [2]

2.1.1 MICROWAVE BASED:

In this technology solar cell mounted on satellite will be generating electrical energy due to sunlight illumination over it, further then electrical energy will be transformed to radio-frequency energy with the help transmitter (antenna) transmit at 5.8 GHz to ground. This concept uses magnetron and impedance matching circuit, whereas magnetron generates microwaves from electrical energy and impedance matching circuit helps to match impedance of microwave with antenna.

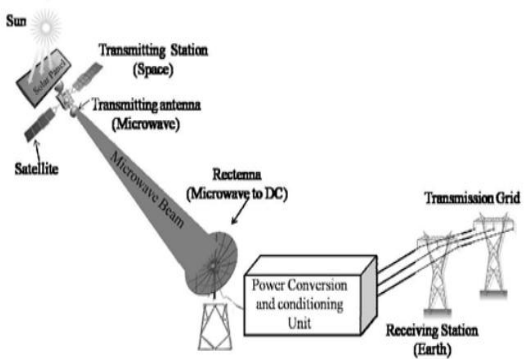

Fig.4 Microwave Based SPS [11]

Now receiver on ground receives microwave radio frequency from space and convert into Direct current (DC) furthermore it is inverted into Alternating current (AC) to feed it domestically and commercially. This receiver is also known as "Rectenna", its combination of rectifier and antenna. To understand this concept Fig.4 represent all the modules which will be used in this technology [11].

2.2 Type-II:

SPS type-II architecture is different from the type-1 sps. This architecture mainly consists of "Laser Technology." Electric laser based is very feasible and in this multiple individual and independent laser platform is provided Fig.5 The only barrier to implement type-II architecture is efficiency. Laser beam will be produced from the solar energy using solid-state laser devices. This laser beam will be collected on ground and will be used to produce electrical energy with smooth transmission [2].

Fig.5 Type-2"Electric Laser" [2]

2.2.1 LASER BASED:

This technology known as "direct solar pumping laser power generation". As per proposed concept of this technology, the energy harvested from the sun by solar cells is used to generate monochromatic (single wavelength) light beam by using "solid state laser medium" shown in Fig.6 such device is used to converts electrical energy into a laser beam.

The generated laser beam pumped to ground on photovoltaic cell as receiver it acts, to make the whole system efficient, a control system is used at the transmitter to point the laser beam all time at receiver on earth. After receiving the laser beam by receiver, it follows the same criteria to generate electrical energy as solar cell does [11].

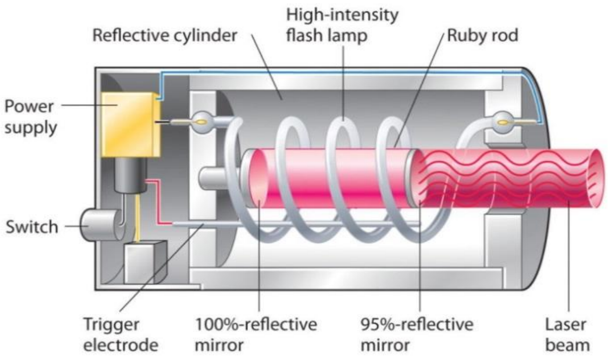

Fig.6 Solid State Laser Device [11]

The depicted module assists in amplifying the photons of specific frequency, and to make the process efficient, sapphire material is used as laser medium or crystal Fig.7

The following picture demonstrates the operation of laser technology [12].

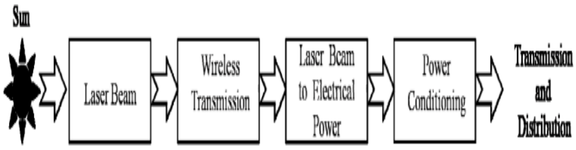

Fig.7 Laser Based SPS [12]

2.3 Type-III:

This design further known as SPS sandwich concept Fig.8 & Fig.9 It employs light redirection concept with modular symmetrical concentrator architecture therefore this concept enhances the architecture and resolve the problem (Power management and distribution system) which was facing in Type-I [8]

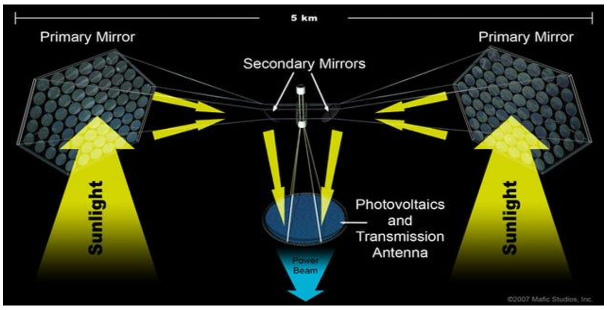

Fig.8 Type-3 "Modular Sandwich Microwave" [8]

The following fig.9 shows the Functional Layer of Modular Sandwich Microwave

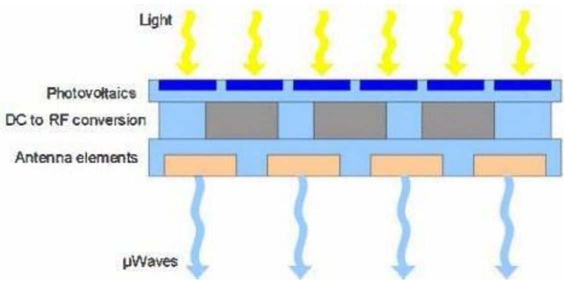

Fig.9 Functional layers of the sandwich module [8]

The sandwich module exhibits some constrains due to irradiative heat transfer relation

$$P = \epsilon \sigma A T^4 \quad (1)$$

Where: -

P is the heat power transmitted

ϵ is the emissivity of the material

σ is the Stefan-Boltzmann constant

A is the radiating area &

T is the temperature module has specified with operating temperature by this each module would be able to "thermally self-sufficient"[8]

2.3.1 HYBRID BASED:

Here both microwave technology and laser technology deploy in this concept, because each technology has merits and demerits, to overcome all issues and to design an optimal module based on their properties the "National Space Development Agency of Japan" (NASDA) has planned hybrid-based concept. In this satellite from the geosynchronous orbit will generate electrical energy and transmit in the form of laser to in-orbit base station, in base station energy converts from laser to electric and electric to microwave radiation. The resultant microwave energy will be transmitted to receiver placed on earth surface. By this laser beam which attenuates in atmosphere can be prevent, whereas microwave has very minute attenuation in atmosphere, hence the efficiency of the plant can enhance by this concept. Following table illustrate about microwave and laser properties [13].

3. PV CELL & REFLECTOR

Space based solar power Consists of so many numbers of solar cells on type-I and type-II architecture, by this power station can be able to generate large amount of power and Type-III uses only one single solar panel with number of photovoltaic cells and abandoned mirrors to reflect light on concentrator, Fig.10 represents these modules were made as a prototype with an efficiency of 28.3% and Ultra Triple Junction (UTJ) Solar Cells technology [8]

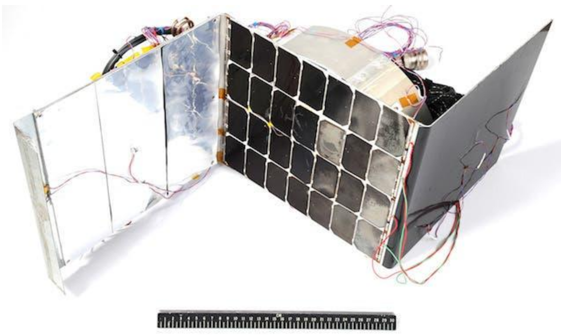

Fig.10 Step modules of PV Cells [8]

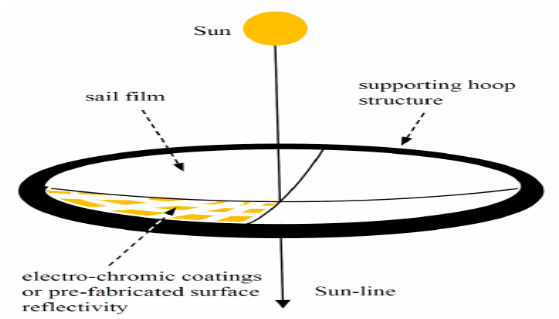

Fig.11Reflector [8]

Reflectors are defined as fixed curved shape with a large spin-stabilized and thin reflective circular film. A parabolic reflector with short focal distance is considered as an ideal shape, and development of such reflectors are also used for important applications in future for instance solar power collection and radio-frequency antennae. Reflector module has designed as inflatable hoop structure as shown in Fig.11

The reflectivity of reflectors can also be modified using electro chromic coatings. As manipulating the surface reflectivity assist in controlling the desire curve shape through SRP. And the equation of referenced parabolic deflection curve is defined as:

$$Y_p = a_p(r2 - R2) \qquad (2)$$

Where:-

p subscript = “parabolic deflection curve r = “derivative along the radial direction”

Y = “vertical load distribution”

R = “hoop radius”

ap = “coefficient”

S = “slack string length”

SRP = “solar radiated pressure”

m = “meter” [9].

4. BEAMING SATELLITE DESIGN

The beaming satellites serve as the hub for both the in-space power and communications grids. For power, they collect the energy being relayed from each of the collectors/sub-beamers and redirect that energy toward Earth using a much more powerful rectenna array that has a considerably large area [2].

For communications, the beaming satellites relay signals not only between the different spokes of the system, but also decipher which telemetry and commands must be relayed to and from the Earth. The most prominent feature of the beaming satellite is the downlink rectenna array. In the system proposed, each collector satellite beams its power to one rectenna array slot. This one-to-one correspondence is designed to minimize interference between the beams of individual collector satellites. The rectenna array on-board the beaming satellite is like the one at the ground station, except for the fact that it is optimized to collect beams of a higher frequency and hence is smaller in size [2].

The support equipment of the beaming array is, in fact, similar to that of the collection satellites. The notable exception is that less structural support for solar arrays is needed. Due to the large size of the collection array, however, the beaming satellites are significantly larger than the collection satellites. The communications equipment aboard the beaming satellites must be more sophisticated to ensure that it can provide sufficient relay capabilities and downlink to Earth [2].

5. POWER BEAMING BETWEEN SATELLITES

The power beaming between satellites will take place at a higher (5.8 GHz) frequency, to ensure that the rectennas on board are smaller and that there is no interference with beaming to the ground. The power conversion efficiency at this stage is assumed to be up to 70%.

The photovoltaic DC to microwave conversion efficiency is 83% [24] and the microwave to DC conversion at the rectenna of the sub-beamer is around 85% [25]. DC to microwave conversion is accomplished through magnetrons or similar devices.

Occasionally, inter or intra spoke beaming can be used for station-keeping or for changing the orientation of satellites within the cluster. Another aspect of power beaming between satellites is the re-use of wasted power during transmission. It has been shown that ambient microwave energy can be reused by a rectenna array with an efficiency of 20% (up to 60% in certain cases) [26]. This recycled energy can be specifically used for the station-keeping needs of the satellite cluster. The incorporation of this feature would be an optional measure for squeezing out maximum overall efficiency from the system.

6. POWER TRANSMISSION FROM SPACE TO GROUND

A word rectenna is made by merging rectifier and antenna. These modules are used as receivers at receiving ground station to harvest wireless power transmitted through microwave radio frequency (RF) and it convert respective energy into direct current (DC),following Fig.12 gives clear comprehension of rectenna [14].

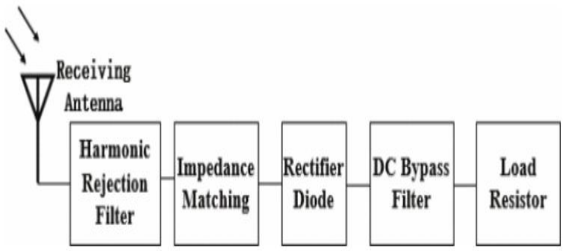

Fig.12 Schematic of Rectenna [14]

Every block has its own significant functionality, whereas receiving antenna receives microwave radio frequency from space and transfer that signal into following blocks one after other to harvest energy from receiving signal in efficient and stable manner, every block does task as per it named [14].

So harmonic rejection filter is used to avoid irradiation of energy into free space, due to irradiation, signal could interfere with other electronic devices which are near to rectenna, if the frequency band of rectenna and electronic device are same. Harmonic filter as well DC bypass filter, eventually it improves the efficiency of whole receiving unit.

To improve the efficiency of power transfer, the transmitter and receiver must have same impedance. Hence impedance matching circuit assist to match the receiver's impedance to get synchronize and to be in same impedance as of transmitter module.

Rectifier diodes are used to convert RF (radio frequency) signal to DC (Direct current) energy. In half wave rectifier or a full wave rectifier, the output of this circuit will be pulsating dc. So, to convert from pulsating dc to pure dc it must go through a filter which filters all ac signals from it and gives pure dc at its output. Equivalently, while converting from radio frequency signal to dc energy the output of filter emits impure signal to filter that it must go through a circuit called DC bypass filter, ultimately the voltage emits from the unit will be stable and constant, which can invert to AC signal based on requirement[14].

$$\beta_S = \frac{180+2\alpha}{360} \quad (3)$$

$$\alpha = \cos^{-1}\left(\frac{R_E}{R_E+h}\right) \quad (4)$$

Here, R_E = 6378.145km denotes earth radius and h is SSP satellite altitude. LEO satellite is considered at the sun-synchronous orbit (SSO)[17], which allows the satellite to be illuminated by sun light for a constant orbit period [18].Based on (3), SSO (650km altitude) and MEO (20200km altitude) satellites have approximate sun light periods of 15.3 and 22.15 hours, respectively. In addition, SSO can be properly designed to ensure approximately 24hrs of sunlight illumination, which is known as full SSO.

Orbit Space	**Sunlight Irradiance**	**Area**	**Harvested Energy**
650km SS	1366 W/m^2	399m^2	2MWh/ day
Full SS	1366 W/m^2	240m^2	2MWh/ day
MEO	1366 W/m^2	260m^2	2MWh/ day
GEO	1366 W/m^2	240m^2	2MWh/ day
Ground	**Sunlight Irradiance**	**Area**	**Harvested Energy**
Global	3.92kWh/ m^2day	1km^2	1.58MWh/ day
Nevada	4.94kWh/ m^2day	1km^2	1.98MWh/ day
Saudi	4.88kWh/ m^2day	1km^2	1.95MWh/ day
Western Australia	5.90kWh/ m^2day	1km^2	2.36MWh/ day

Table1: Power transmission from space to ground [17]

Solar power that is harvested in space and on the earth respectively corresponds to:

$$P_{Space} = \eta_{PV} \times \eta_{DC-RF} \times I_{Space} \quad (5)$$

$$P_{Earth} = \eta_{PV} \times I_{Earth} \quad (6)$$

$$I_{Space} = \beta_s I_0 \quad (7)$$

In (5), η_{DC-RF} denotes the direct current (DC) to radio frequency (RF) conversion efficiency, which is assumed 80% [20], in (5) and (6), η_{PV} denotes solar cell energy conversion efficiency, and in (7) I_0 is solar irradiance, which is 1366Wm-2 hr-1 [18], Table2 shows the total power generated per day as follows

Orbit	**400m^2 Panel**		**1200m^2 Panel**	
	In Space (per day)	**By Ground (per day)**	**In Space (per day)**	**By Ground (per day)**
650km SSO	999 kWh	669 kWh	3.00 MWh	2.01 MWh

1000km full SSO	1.31 MWh	541 kWh	3.93 MWh	1.62 MWh
MEO	2.90 MWh	1.88 kWh	8.70 MWh	5.64 kWh
GEO	3.15 MWh	0.54 kWh	9.44 MWh	1.63 kWh

Table2: Total power generated per day [17]

The ground solar power plant is assumed to have a total of 1km2 solar panel with concentrated PV technology, and efficiency of 40% based on results depicted by Spectorlab [21]. The annual average sunlight irradiance (see TABLE 1) can be obtained from [22] (up to year 2005). TABLE 1 shows that the maximum solar energy of 2.36MWh per day harvestable at Western Australia, while other regions can only harvest less than 2MWh of energy per day. Here, we consider the Azur Space thin film solar cell for space applications [23], with has the efficiency of 30%.

Using β_s computed in (3), TABLE 1 shows that at SSO, only 399m 2 of solar panel area is required to achieve a total harvested energy of 2MWh per day. This indicates that less than 1% of total area is required compared to the ground based solar power generator. If the satellite is illuminated by sun light for near 24 hours every day, such as either full SSO or GEO, then 240m2 of solar panel area is required.

The regular SSO requires larger solar panel area because there is approximately 9 hours per day under earth eclipse. MEO satellite requires lower total solar panel area compared to regular SSO because higher altitude maintains a shorter eclipse period.

7. HIGH VOLTAGE TECHNIQUES

Solar cell array has divided into sub array, each sub array is of 10 photovoltaic cell, every sub array is connected with centralized high voltage converter and the output of converter is given to rotating contact, whereas each rotating contact can be connected at a time with 10 centralized high voltage converter, which is called as “photovoltaic cell division unit”, further microwave transmitters are connected with rotating contact on transmission bus to transmit sub array’s energy, by this system’s reliability improves and “single point failure can be avoided”. By observing following Fig.13 & Fig.14 the above description can be easily understood. And the scheme of combining modular multi converter in series and parallel use to boost up the voltage. If one converter gives 10V output voltage and then if we connect 10 converters in series therefore the overall output voltage would be 100V and it can be controlled by adjusting sub array. By this it is easy to achieve high voltage without using high voltage conversion module [15]

International Journal of Advance Research in Science and Engineering
Volume No. 11, Issue No. 02, February 2022
www.ijarse.com
IJARSE ISSN 2319 - 8354

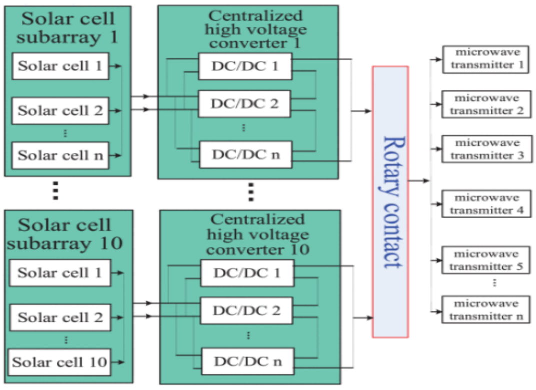

Fig.13 Hybrid power management and distribution mode [15]

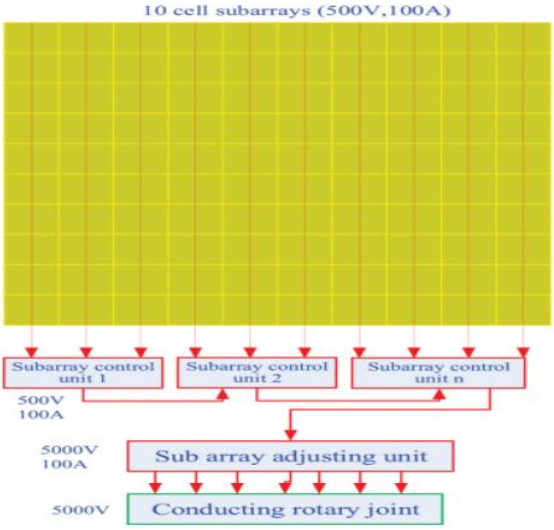

Fig.14 High voltage transformation topology [15]

8. FREQUENCY

Between 1-6 GHz is the optimal frequency to use for power transmission with microwave in state space power transmission, beyond this respective frequency attenuation may become larger which would be not efficient for power transmission.

Therefore, frequency of Industrial, scientific and medical (ISM), either 2.4GHz or 5.8 GHz would be efficient and best for transmitting power in microwave form. From the recent study 5.8 GHz has more supportive properties than 2.4 GHz. On the other hand, laser technology uses 1.06 µm frequencies for transmitting power from space to ground [13].

9. CONCLUSION

This paper summarizes the space-based solar power generation & distributed network concept which overcomes our problems, such as environmental issues and lack of power generation for inhabitants. By this technology, it is possible to obtain power 24 hours without any effects of day and night, with a clean and neat process. The power can be transmitting any point in the globe wirelessly to the receiving stations at different locations.

Moreover, space solar power systems appear to possess many significant environmental advantages when compared to alternative approaches. The only issue would be capital cost, which is not economical up to now. Space solar power may well emerge as a serious candidate among the options for meeting the energy demands of the 21 centuries.

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