IAC-21-C3.1.8

A NOVEL APPROACH TO MEET FUTURE ENERGY NEEDS: SOLAR POWER SATELLITE

Lekhashree H J[a]*, Ananya Kodukula[b], Dharini Raghavan[c], Sujatha B[d], Shailendra Sorout[e]

[a] *Department of Electronics and Communication Engineering, Ramaiah Institute of Technology, Bangalore*
[b] *Department of Computer Science and Engineering, Ramaiah Institute of Technology, Bangalore*
[c] *Department of Electronics and Communication Engineering, Ramaiah Institute of Technology, Bangalore*
[d] *Associate Professor in Department of Electronics and Communication Engineering, Ramaiah Institute of Technology, Bangalore*
[e] *Department of Electronics and Communication Engineering, Ramaiah Institute of Technology, Bangalore*

* Corresponding Author

Abstract

It is widely agreed that our current energy practices will not provide for all the world's population adequately and still leave our Earth with an available environment. Hence, it is now a major task for the new century to develop sustainable and environmentally friendly sources of energy. The main objective of the Solar Power Satellite (SPS) is to convert solar energy in space for use on Earth. It is more advantageous because it can continuously generate large-scale electric power for distribution on a global scale. The SBSP system is outlined, and the status of the SBSP concept development is reviewed. The Solar Based Solar Power (SBSP) Satellite system can deliver power to space vehicles as well as to elements on planetary surfaces. International SPS-related activities within the context of evolving space programs from 1970 will be discussed briefly. An approach for an evolutionary advancement of SBSP to meet requirements of power supply for use on earth and in space is presented, and a growth path to achieving the more efficient power from space for use on earth is outlined. This paper will present the brief concept evolution of a satellite power system and the impact of microwave power transmission on space plasma. In near future, conventional power sources cannot meet total power demand, for which SPS proves to be a viable solution. This paper answers the fundamental question of why there is a need to develop SPS from the viewpoint of critical global issues surrounding mankind, the advantages, disadvantages, and biological impacts on Earth in a comprehensible manner. The significance of advancements in technologies applicable to the development of the SPS will also be discussed.

Keywords: solar power satellite, microwave power transmission, space plasma, electric power, conventional power sources, solar energy

Acronyms/Abbreviations

UN	United Nations
SBSP	Space-Based Solar Power
SPS	Solar Power Satellite
NASA	National Aeronautics and Space Administration
JAXA	Japan Aerospace Exploration Agency
DOE	United States Department of Energy
ISRO	Indian Space Research Organization

1. Introduction

The whole world is run by electricity. Urbanization has increased the energy demand due to the growth in the world's population, economy, and needs. The United Nations (UN) estimated that the world's population will grow up to 9.7 billion by 2050. Energy and Environment are considered important issues in this technologically growing world. It is known that approximately 80% of energy comes from fossil fuels. If we continue to use fossil fuels at the present consumption rate, oil, natural gas, and coal may completely run out within 50-100 years. Everything in the world is run by electricity. In the 20th century, the prices of resources were comparatively low. The population has increased and developing and underdeveloped countries are improving their living standards. So, the cost of resources is increasing rapidly. Apart from the cost factor, the major concern is about the environment. Fossil fuels greatly contribute to the greenhouse effect and global warming. Fossil fuels are non-renewable, once it is gone it can't be obtained back. So, the world must think about the solution before it runs out of energy sources. The ideal solution for this problem is energy that is renewable, easily accessible, independent, clean, and at a low cost. This global problem can be effectively solved by a powerful energy source, the Sun. Using the concept of space-based solar power generation technique we can generate a huge amount of power to meet the future global energy requirements [1]. In 1968, Peter Glaser and in 1974 Arthur D Little proposed the concept of Space-Based Solar Power (SBSP) to meet the future global energy needs. Glaser's idea was to place a large solar array in a geosynchronous orbit and transmit the power to the earth in the form of a microwave beam [2]. Rectifying antenna also called "Rectenna" are placed on the ground at the receiving end to receive the beamed power. These rectennas convert microwave to electrical power. Most of the SPS models uses microwave for wireless power transmission since more efficient power will be produced both at transmitter and receiver end. Also, there will be lower attenuation through the atmosphere for the microwave when compared to lasers. The main reason to choose space for placing solar panel array instead of the ground is if the solar panel is placed on the surface of the earth, by the time the solar energy reaches the surface of the earth it will be filtered by the atmosphere and the day-night cycle. The amount of power would be very less. So, by placing a solar array in space full sunlight without any interruption can be obtained. In the late 1970s, NASA researchers found that the whole project of SPS would be too expensive. But, after over 40 years the study got importance since the space launch cost was significantly reduced due to the implementation of new technologies. Elon Musk's SpaceX has brought a tremendous change in the space industry due to re-launchable vehicles. The increase in energy cost and the increase of exhaustion of fossil fuels has led to an increase in global warming and greenhouse effect the given light to the concept of extracting renewable solar energy to produce electricity.

2. Literature Survey

2.1 Basic timeline of SPS

In 1968, Dr. Peter Glaser and Arthur D Little proposed the concept of placing Solar Power satellites in Geostationary Earth Orbit (GEO) to generate solar energy and transmitting the solar energy in the form of microwaves with a frequency of 2.45GHz. In 1970s, the US Department of Energy (DOE) and NASA- National Aeronautical Space Administration examined the concept of SPS. They examined the environmental effects and their technical, social, and economic impact. In 1981, Japan developed an idea about space solar power. With reference to NASA's space solar satellite system, Japan developed a 10MW photovoltaic solar power satellite. In the 1990s, NASA conducted a study on Space Solar Power (SSP) technology. In 1999, NASA began a Space Solar Power Exploratory Research and Technology (SERT) to conduct further research on space-based solar power. SERT conducted several kinds of research on space-based solar power satellites, their applications, and their commercial uses. Due to the massive expansion of the space research industry many countries are currently researching on the SBSP system. In 2007, a workshop to review the current state of SBSP was held at the Massachusetts Institute of Technology-MIT (US). In 2010, Indian Space Research Organization (ISRO) and US's National Space Society jointly launched a forum to obtain solar energy using space-based solar collectors known as the Kalam -NSS Initiative, which is named after the former Indian President Dr. APJ Abdul Kalam. In 2012, during Dr. Kalam's visit, China joined hands with India for developing SPS. On 12th March 2015, JAXA announced that they beamed back 1.8KW power to a small receiver by converting microwave to electricity [3]. In 2019, Aditya Baraskar and Prof. Toshiya Hanada from Space System Dynamic Laboratory, Kyushu University, gave a proposal about E-Orbit. The constellation of small solar Power Satellite beamed power from the satellite to the Low-Earth orbit. In 2019, China announced a plan to launch a working megawatt grade 200-tonne SBSP satellite by 2035. In 2021, USAF's Space Solar Power Incremental Demonstration and Research Project (SSPIDR) is planning to launch the ARACHNE test satellite in 2024. In 2021, the famous Caltech announced that it has planned to launch an SBSP test array by 2023.

2.2 Overview of previous models

The worldwide power demand has led researchers to think of various techniques for efficiently extracting power. Various organizations such as NASA, JAXA, International Astronautical Congress (IAC) Space Power Committee, the International Conference on SPS [4], and WPT are working for the development of powerful SPS systems. A few of the models are presented in the following section.

2.2.1 NASA Reference Model

This was the first SPS system that was designed which was led by NASA and DOE as the reference model of GEO solar power satellite is shown in Fig 1. This system consists of a huge solar panel with 5km×10km size and generates DC power. The diameter of the antenna used is 1km. This system was huge in dimension and the size of the antenna was large so it required a huge amount of human effort and cost. This surpasses the budget allocated.

Fig 1. Artist rendering of NASA reference system

2.2.2 SPS launch from space

Due to high costs involved in launching a SPS system to ground, Gerard O'Neil came up with an idea to launch SPS from the moon. This is because the moon has lower gravity compared to earth so it requires a much lower cost to launch SPS. In 1979, the General Dynamics Convair Division gave the final report and concluded that lunar resources for SPS would be much cheaper as compared to Earth-based materials [5]. In 1980, Gerard O'Neil once again came up with the new idea of SPS which required less human influence and it was working on a self-replicating system. This system was less bulky than the original SPS system.

2.2.3 SPS 2000

One of the most prominent SPS projects was the Japanese SPS 2000 project which uses wireless power transmission technique. The Fig 2. Shows the Conceptual model of SPS 2000.The main aim of this project was to construct a more efficient space solar power satellite system. It consists of a large rectenna on the ground station. This was designed as a gravity stabilizing satellite that could deliver 10MW of electric power from a spherical 1100km east to west equatorial orbit [6]. The transmitting phased array of the antenna was designed to steer ±30º along the east-west or along the orbital path and steer ±16.7º perpendicular to the orbital path. The rectenna must be somewhere close to the equator. During an eclipse, on an average daily coverage of fewer than 30 minutes per site energy of 4MWh to 4.5MWh would be available for SPS 2000.

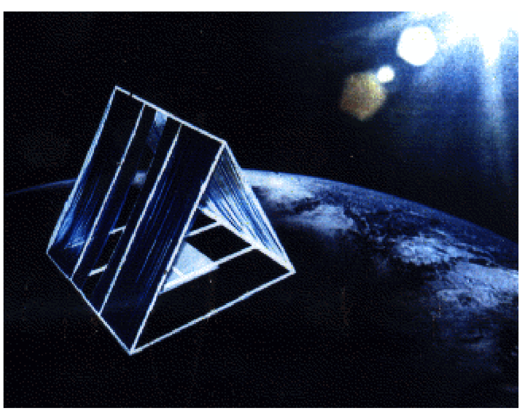

Fig 2. Conceptual model of SPS 2000

2.2.4 ISPER Project

Japanese space agency wanted to build a powerful SPS system using new technology. The main aim of this project was to prove the operation of an antenna photovoltaic array in space [7]. The design was based on the idea to integrate solar cells in a retro-directive solid-state phased array transmitter and to transmit the power to smaller satellites which are placed in Lower Earth Orbit (LEO) and then to the ground receiving station. The Fig.3 shows a diagrammatic representation of the sandwich model proposed by ISPER [8].

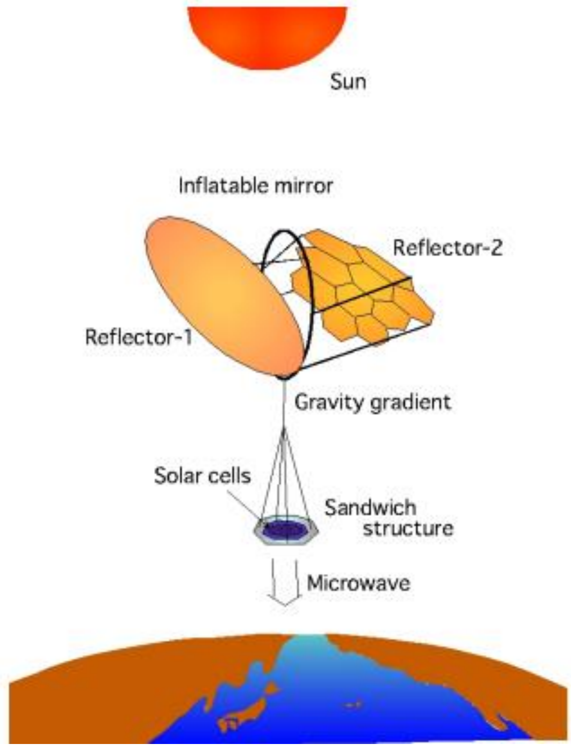

Fig 3. The concept of the SPS with the sandwich panels

2.2.5 Retro-directive phased array antenna/rectenna model

Kobe University demonstrated an experiment on SPS to develop a system with less weight and small size SPS and to get more efficient power. The design included a 5.8GHz retro-directive phased array power system. This used a solid-state amplifier that was directly connected to the transmitter. It used phase shifters which combined with conjugate phase to beam back the microwave accurately to the rectenna.

2.2.6 CASSIOPeiA phased array antenna

This model of phased array antenna was proposed for a spacetenna. The main aim of this model was to solve the difficulty in mechanical direction control of spacetenna by installing rows at different angles as shown in the Fig.4. It is designed such that it contains three radiating elements which form a radiating unit and it has a separation of λ/4 which results in an excellent radiation characteristic of horizontal uniformity [9]. These array with radiating units of horizontal direction by phase control

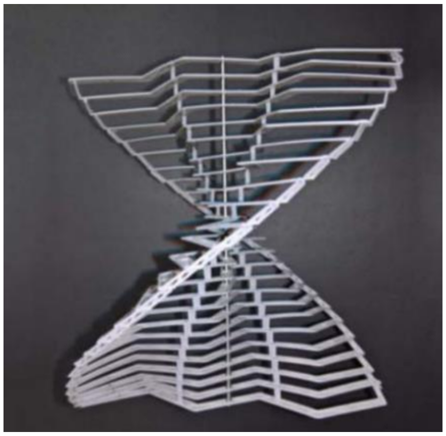

Fig 4. CASSIOPeiA phased array antenna

2.2.7 Tethered unit model

This model was designed in Japan, this model was designed such that SPS was located in GEO shown in Fig 5. The spacetenna's faces to the ground by virtue of gravity gradient stability. In this system, solar cells were attached to the backside of antenna modules. The main aim of this model was to get more functional SPS for future use.

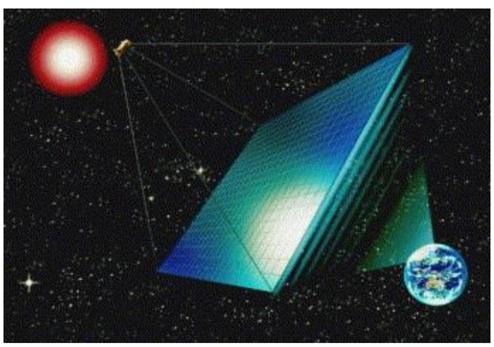

Fig 5. Tethered SPS - USEF

3. Theory and calculation

The main aim of these satellites is to collect solar energy using solar cells and it will convert sunlight to DC. Then the DC is converted to a radio-frequency wave by a transmitting antenna and beamed back to earth. This radio frequency is then converted back to DC using receiving antenna, also called "Rectenna". This is clearly shown in Fig.6. Then the electricity will be sent to the standard power grid for use on earth.

3.1 *Functional Units of a Solar Power Satellite*

3.1.1 *Space Satellite*

Converts solar energy to DC. It mainly consists of a solar cell array, battery backup system, and tool for power conversion [10]. The solar array will be paired with a reflector array and it will concentrate solar energy to photovoltaic cells [11]. Photovoltaic cells directly convert photons into electricity using semiconductors.

3.1.2 *DC to Microwave Conversion*

Microwave oscillators such as Klystrons and magnetrons are used to convert DC to microwave for transmitting the beam through Antenna. In most cases, magnetrons are used because they are highly efficient at a cheaper cost. Magnetrons can convert electron beams and can transmit microwave beams within a given frequency range. The magnetron is a diode-type electron tube, which uses the interaction of electric field and magnetic field in a complex cavity to produce oscillation of high peak power.

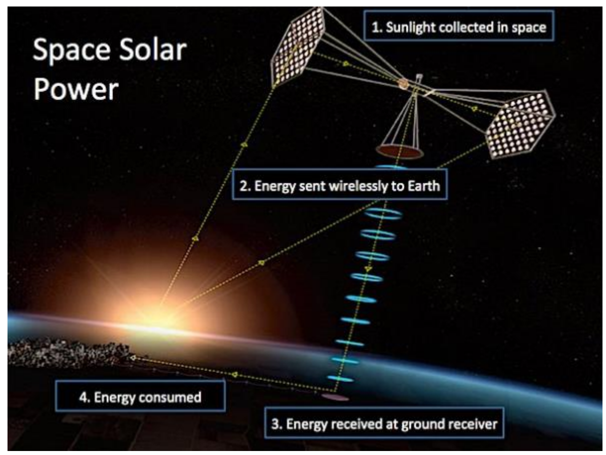

Fig 6. Solar power satellite system

3.1.3 *Wireless Power Transmission*

Space Solar Power Satellite Transmits the microwave beam to earth through Wireless Power Transmission (WPT) mode. SBSP is designed to obtain efficient power transmission from space to earth. It consists of a gigantic antenna array to beam down the microwave power to the ground station. Microwave Power transmission is considered more efficient than the laser, as it undergoes less atmospheric attenuation due to dust, rain, cloud, water vapor, etc [12]. Electrical conduction and resonant induction methods are widely used because it allows elimination of existing high tension power transmission lines and the global scale interconnection of power generation plants. Amplitude taper can be used to increase the efficiency of beam collection and decrease the sidelobe and is used to prevent unwanted transmission radiation on the ground [13].

3.1.*4 Ground Antenna*

Microwave beams are beamed back towards the ground on a large array of parabolic antennas used to track the satellite SBSP. This array has wide-spaced poles and cables in between them and some inexpensive modules [14]. The Power received is conditioned and it can then be sent to grid for the use on earth. The land below the ground antenna can be utilized for agriculture and some other purpose.

3.1.5 *Rectenna*
Rectifying Antenna also known as Rectenna. The SBSP Satellite system needs a large area with a Rectenna array and a power network that will be connected to the existing power grid [15]. Rectennas can receive microwave beams from space and can convert them back to low-frequency DC power. Rectenna is a passive element. Its main components include an antenna, rectifying diode, and DC bypass filter. Agricultural activities maintaining farm animals can be raised beneath a rectenna. The electricity obtained is fed into the existing commercial power distribution grid. Only a few days during the equinox period that is during spring and fall equinox the satellites will be in shadow. It will be in shadow for less than 1% time in the year. Power can be beamed back into the location where it will be required.

3.2 *Merits*
1. Solar power is renewable and non-exhaustible. Fossil fuels are limited in nature but space solar power is an unlimited source of energy.
2. Pollution-free: Unlike fossil fuels, space-based solar power doesn't emit Carbon-dioxide and greenhouse gases which result in global warming.
3. It is easy to transmit the microwaves generated in space back to earth. Which will then be converted into DC and then it can be transmitted anywhere on the earth.
4. Better than Nuclear Power: Space solar power doesn't produce hazardous waste products and it is not targeted by terrorists [15].
5. Mining is not required: Mining is an environmentally tedious process. SBSP does not require mining which becomes a major advantage.
6. It has high Transmission efficiency: By using the wired transmission technique most of the power is wasted during transmission. Since transmitting microwaves through wireless transmission mode, provides higher transmission and conversion efficiency.
7. Harmless radiations are produced which are safe for humans and the environment.
8. Since the system is placed in space it can't be disturbed or interrupted by plants and animals.
9. Ground solar power is interrupted by day-night cycles, whereas the SBSP system is interrupted by shadow only for 75 minutes and spring and fall equinox. So SBSP has the maximum power-producing capability [6].

3.3 *Demerits*
1. The major disadvantage would be because of space debris. Since the SBSP system is quite a large structure there may be a potential source of orbital debris. Already geosynchronous orbit is highly used, it could be in an endangered position by space debris [16].
2. This SBSP system is quite expensive to maintain.
3. Installing large materials in space would be expensive and challenging.
4. Due to the hostile space environment, panels are prone to degradation.

3.4 *Theoretical Design of a typical SPS*
3.4.1 *Mission Description*
The combination of sun-synchronous orbit, three femto-satellites in a constellation of satellites at an orbit of 792km, the Hub at an altitude of 792.5km, and a revisit time of 12 hours, serves the requirements provided by the objectives of this mission. The sequence of the mission is as follows:
1. The Hub houses 3 femto-satellites, till the desired orbit of 792km.
2. After the successful deployment of the femto-satellites, the Hub propels itself to an orbit of 792.5km in order to keep in pace with the femto-satellites.
3. Once the Hub and the set of 3 femto-satellites will take up their respective configuration, they begin to work together towards fulfilling their respective objectives.
4. The objective of the femto-satellites is to convert solar energy to DC.
5. This Hub then behaves as a communication node between the femto-satellites and the Ground station. It also houses a larger-sized solar array cell for the desired function of solar energy to DC conversion.

3.5 *An overview of subsystems in a typical SPS*

3.5.1 *Electrical Power Subsystem*
Its major function includes generation, storage, distribution, and control of electrical power required for the entire mission. The major objectives of the electrical subsystem are to provide an intermittent source of power to all the components at a required point of time, distribute power in a regulated manner, prevent faults and failures in the electrical power system and satisfy the power requirements of all the other subsystems. For the SPS mission, typical components for the satellite and the HUB segment include lithium-ion battery and germanium arsenide solar panel. The following Fig 7, gives the basic idea of the schematic employed in the power transmission module.

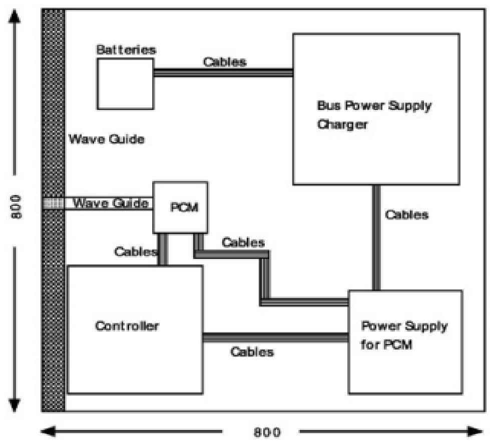

Fig 7. Configuration of the components in the power generation/transmission module

3.5.2 *Attitude determination Control System (ADCS)*
Attitude determination and control is the system responsible for the stabilization of the satellite and its prime function is to maintain the desired orientation of the satellite in space. It is quite challenging to ensure the proper functionality of the satellite in space due to unpredictable conditions in space. High accuracy should be achieved at the same time to satisfy the mass and power restraints. Typical components as a part of this subsystem shown in Fig 8, and Fig 9 are Sun Sensor (OPR5910 photo diodes), Magnetometer (Xtrinsic MAG301 3-axis) and gyroscope (ITG 3701 3-axis) for the satellite segment and Sun Sensor (OPR 5925 Quadrature photo diode) and Integrated Measurement Unit (Vector Nav VN 100) for the HUB segment.

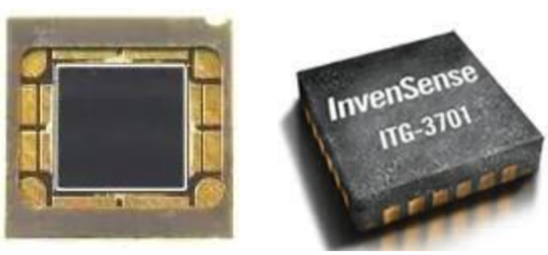

Fig 8: Sun Sensor (OPR5910 photo diodes), Magnetometer (Xtrinsic MAG301 3-axis)

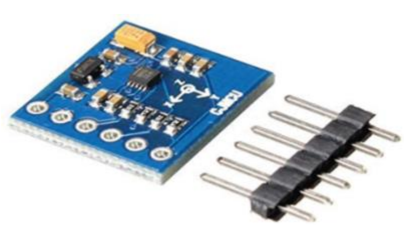

Fig 9: Gyroscope (ITG 3701 3-axis)

3.5.3 *Communication*
The communication system is one of the most important part of the satellite. It establishes a way of receiving and transmitting data from the ground to the satellites and vice-versa. The signal received by the satellites from the ground stations is known as the uplink and the signal transmitted by the satellites to the ground station is known as the downlink. The design of Earth recieveing station is shown in Fig 10 [15]. This communication is a two-way process. The signal is transmitted as radio waves. When it comes to a communication relay model, timing and attitude play a major role. Depending on the efficiency of conversion required different types of the antenna can be used for the transmitting antenna and the rectenna.

Fig 10: Design of Earth Receiving station

3.5.4 *Position Determination System*
The location of the satellites are determined using tracking from ground stations. The ground stations use mechanism such as radar, signal Doppler, and laser reflectors to pinpoint the position of a satellite and to maintain an understanding of its orbital elements. Instrumentation involved in this subsystem is GNSS 200 Series Global Navigation Receiver shown in Fig 11, for the and Space GPS Receiver SGR 05P for the HUB.

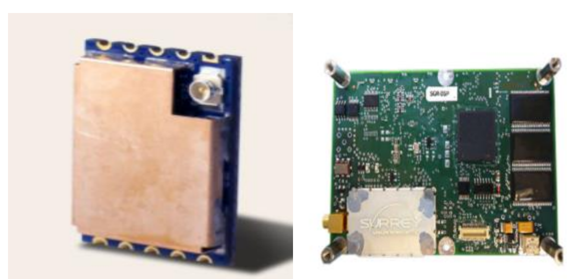

Fig 11: GNSS 200 Series Global Navigation Receiver(left) Space GPS Receiver SGR 05P(right)

3.5.5 *Structure and Thermal Subsystem*

The design considered for the femto-solar power satellite is based on the dimensions of the components chosen to be mounted on the PCB. Each component is separately designed and assembled in order to bring a visual aspect to the femto- satellite. Since the circuits and peripheral components were not considered, approximate dimensions are taken in order to place the components on the PCB. The final design of the femto-satellite is dependent only on the mass and the volume budget. Aluminum 7075 or 6061-T6 is suggested for the main structure in the system. If other materials are used, the thermal expansion coefficient must be similar to that of Anodized Aluminum 7075-T3. It has properties like resistance towards corrosion, avoids stay light in optical equipment, is scratch-resistant, good surface finish, and is low in weight.

4.Results

This paper has aimed to present an overview of the importance of Solar Power Satellites and how this satellite technology has grown throughout the years. The paper first briefly discusses previous SPS missions, merits, and demerits of SPS systems, followed by typical functional requirements for an operational SPS. The paper has also aimed to provide a theoretical model of a general femto-satellite-based SPS system describing the components required as a part of different subsystems.

5. Conclusions

The increase in the global energy requirement has led to the depletion of fossil fuels. This results in to increase in the price of these fossil fuels like petrol, diesel, oil, etc. So, now people are searching for an alternative energy source. The SBSP can generate safe, clean, and pollution-free power which can meet electricity demand for the future generation. SPS can collect solar energy directly from the sun and transmit that to the earth wirelessly in the form of a microwave beam. Then the power can be used all over the world. The SBSP has more advantages than ground-based solar power. SBSP can also help to reduce fossil fuels and reduces the emission of Carbon-dioxide and thereby reduces global warming. If some of the technical, economic, commercial, and environmental issues of SPS are solved we can implement this idea successfully to meet future energy needs.

Acknowledgements

We would like to take this opportunity to thank the International Astronautical Federation (IAF) for hosting the 72nd International Astronautical Congress, Dubai and giving us a platform to present our technical papers and above all, a chance to network, learn and grow.

We also thank our faculty mentors for guiding us throughout the course of preparing this technical paper. Special thanks to Ramaiah Institute of Technology and STARDUST RIT for providing their unwavering support. We would also like to thank our family and friends for their encouragement.

References

[1] Seth Potter. "Solar power satellites: an idea whose time has come.", Space Future , Jan. 12, 2004 [Jun. 20, 2019J.

[2] Peter E. Glaser. "An Overview of the Solar Power Satellite Option." IEEE Transactions on Microwave Theory and Techniques, VOL 40. NO 6, June 1992

[3] M. Nagatomo, S. Sasaki, Y. Naruo and VA Vanke, "Solar Power Systems (SPS) investigations at the Institute of Space and Astronautical Science of Japan." Feb. 18, 1994

[4] S Sheik Mohammed , K Ramasamy., "Solar Power Generation using SPS and Wireless Power Transmission", International Conference on Energy and Environment, March 2009

[5] David R. Criswell, "Overview of the proposed lunar-solar power System," in WPT-93: First Annual Wireless Power Transmission Conference, Center for Space Power, Texas A&M University, College Station, Texas, pp. 223-231, 1993

[6] K.S Anagh, K. S Ramshesh, J Pourush, "Solar Power Satellites", International Journal of Engineering Research & Technology (IJERT), ISSN: 2278-0181 May 2013

[7] Jonas Don-yelee Dakora, Innocent E Davidson, Gulshan Sharma, "Modern Solar Power Satellite Systems", IEEE Xplore, 2020

[8] Paul Jaffe, James McSpadden, "Energy Conversion and Transmission Modules for Space Solar Power", Proceedings of the IEEE, April 2013

[9] Tadashi Takano, "Antennas for Microwave Power Transmission from a Solar Power Satellite to the Earth", IEEE Indian Conference on Antennas and Propogation (InCAP), **DOI:** 10.1109/InCAP47789.2019.9134629, 08 July 2020

[10] G. A. Landis, "Solar Power From Space: Separating Speculation from Reality," in Proc. Of the 21st Space

Photovoltaic Research and Technology Conference, Cleveland, OH, 2009, pp. 320-328.

[11] Geoffrey A. Landis. "An evolutionary path to SPS," in Proc. Space Power, 1990, vol.9, no.4, pp.365-371

[12] Matsumoto. "Research on solar power satellites and microwave power transmission," IEEE microwave magazine, vol. 3, no. 4, pp.36-45, Dec. 2002

[13] Susumu Sasaki, Koji Tanaka, Advanced Mission Research Group, "Wireless power transmission technologies for solar power satellite", IEEE MTT-S International Microwave Workshop Series (IMWS), ISBN:978-1-61284-214-1, June 2011

[14] Shu Ting Goh, Seyed A. (Reza) Zekavat, "Space Solar Power Orbit Design and Cost Analysis", 2015 7th International Conference on Recent Advances in Space Technologies (RAST), June 2015

[15] Thorat Ashwini Anil, S.S Katariya, "Solar Power Satellite", IOSR Journal of Electronics and Communication Engineering, ISSN: 2278-2834, pp: 59-64

[16] ShreyAnant Sandiman, Ritesh Diwan, "A review article of Solar Power Satellite.", International Journal of Engineering Research Technology (IJERT), November, 2018