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Revolutionizing Solar Power: Enhancing Transmission Methods for Space-Based Systems

Pinaki Banerjee[1], Lavesh Mathur[2], Jatin Balraj Dalmotra[3], Harsh Kari[4]

[1,2,3,4]University Institute of Engineering, Aerospace Engineering, Chandigarh University, Mohali, Punjab, India

Abstract
Energy has been the first and foremost priority of human beings since the industrial era and afterwards. We have always focused on using minimum energy and saving it as much as we can considering the impacts of our technological advancements on our environment. This has played a crucial role in space exploration as well which, with time, has a lot of benefits. The usage of energy in our day-to-day lives has been increasing exponentially, adversely affecting our biosphere, which is estimated to increase more in the coming time. The need of the time is to minimize this energy input and switch ourselves to more natural and ever-lasting energy generation methods. Outer space exhibits everything that humanity depends upon. So, it is beneficial to utilize something directly from the space itself and not the non-renewable fuels. By providing the necessary energy, space-based solar power technology will aid in the pursuit of sustainable objectives and environmental planning. As a result, research on space-based solar power has gained prominence in the aerospace industry. Solar energy is often captured by solar collectors or the light structures of solar arrays in SBSP, and electronics devices then transform it into another kind of energy, such as microwave or laser, for transmission to Earth. Compared to other energy sources, the microwave is safer for living things. A lot of people who are interested in space and creating new ideas have been drawn to the concept of producing solar electricity from space.

Keywords: Industrial, Solar Electricity, Space-Based Solar Power Technology, Microwave Transmission, Environmental Planning

I. INTRODUCTION

A good proportion of power these days is being accomplished using renewable resources in the form of Solar Energy, Wind Energy, thermal energy, etc. Among many of these the most widely used process is collecting Solar energy and converting it into useful forms according to our needs. The obvious way to do this is by using solar panels in which the photovoltaic effect occurs causing the electrons to move in a single direction producing electric current which is then harnessed by inverters and used in homes. But the power generated by the solar panels depends upon many factors such as the availability of sunlight, weather, and climatic conditions of the place, etc., also, the need for power has been increasing exponentially with the increase in human needs.
The concept of space-based power is the collection of Solar power in a fixed orbit of Earth by using a Solar Power Satellite (SPS) which then transmits it back to the ground station after converting it to microwaves. Solar energy is converted to microwaves outside of our atmosphere in the SPS itself. Microwaves of the electromagnetic spectrum that have less opacity are then collected using specific

antennas and then converted to the power of our specific needs. About 55-60% of this converted solar energy is lost while being transmitted due to absorption and reflection through different atmospheric layers. This process of collecting and converting solar energy is clean and large because of no dependence on the atmospheric conditions of our planet and the long duration of nights.
The small size of the individual satellites will not contribute the energy we need; therefore, this requires at least 100 launches in space of small satellites which would be self-assembled, and because of the low power of each individual satellite, this would result in higher production costs in tens of billions of dollars. Since the assembled satellite is to be placed in geostationary orbit, it is very tough to repair the SPS in case of any technical failure or damage.
This method is relatively cheaper and very productive. At the start, the start-up cost can range from $500 million to $1 billion, and alternate single launches would lower costs and risks when self-assembled. There would be a continuous transmission of power that cannot be bothered by our atmospheric conditions and the transmission would be safe. The laser beam's narrow diameter would make ground implementation easier and less expensive. This can deliver energy nearly up to 1 GW, which is sufficient to power a city. This makes Space-Based Solar Power an efficient way to fulfil our needs and would be healthy for our planet's environment.

II. LITERATURE REVIEW

With the rise in environmental issues such as global warming and climate change, using alternative sources of energy has become the need of the hour. This is mainly because non-renewable sources of energy such as fossil fuels, etc. cannot last long and they are at the constant risk of unavailability. Hence, renewable, or alternative sources of energy have become necessary for power generation. However, tapping alternative sources of energy is comparatively less efficient than the non-renewable ones. For instance, solar energy is a very useful energy source but cannot be tapped at night. Thus, to overcome this defect, a new form of power generation was introduced by Peter E. Glaser, an American scientist, in a technical paper published in 1968 which is known as the 'Space-Based Solar Power.
In a United States Army War College journal titled 'Space-Based Solar Power: A Technical, Economic and Operational Assessment' by Jeffrey L. Caton, the concept of space-based power has been precisely explained as the system in which solar radiations are collected and converted to microwave radiations in outer space on a satellite system. This microwave energy is then transmitted to Earth and converted to electrical power for distribution. The entire journal has been written by division into the following three categories:
a. Technical Assessment: This category discusses the complete concept of space-based solar power (SBSP) and provides a detailed summary of the evolution of the concept, which has been documented in six reports ever since the concept was first introduced in 1968. It also carries out a careful examination of the various critical technologies needed for the successful development of space, support, and ground aspects of the system.
b. Economic Assessment: This category carries out an examination of the cost estimates of the SBSP system from various sources. It then carries out a comparison of these costs to the currently available alternative energy solutions such as terrestrial-based solar energy power plants. The category also discusses regulatory factors that may affect the development and operation of SBSP systems as well as currently undergoing international efforts in this field.

c. Operational assessment: This category explores the strategic usage of SBSP systems within the context of space operations within nations. It then discusses potential applications and compares them with the current plans of the United States Army's Energy Initiatives Task Forces to integrate terrestrial-based power into the energy systems of several major installations. Also, it briefly explores possible SBSP applications to support remote operating locations that would prove to be useful in various military operations across the world.

A 2015 paper named 'A Study on Space-Based Solar Power System' by Anveshi Atul explains in its methodology that researchers are planning to design and develop a Space-based solar farm that would generate 1 GW of power and allow it to transfer back to the earth through microwaves or even lasers. This will require an area of 4 sq. km consisting of several rows of solar panels. This space solar farm will be housed 36,000 km above the earth's surface. It has explained in further detail that space-based power designs generally include the use of some manner of wireless power transmission. The collecting satellite would convert solar energy into electrical energy on board, powering a microwave transmitter or laser emitter, and focus its beam on a collector (known as rectenna) on the earth's surface. The paper's design section explains that the SBSP system essentially consists of three elements:

A. A means of collecting solar power in space, for example, using solar concentrators, solar cells, or a heat engine.
B. A means of transmitting the collected power to earth, for example, using microwave or laser.
C. A means of receiving the power on earth, for example, using a microwave antenna (known as the receiving antenna or rectenna).

It also mentions that the system need not support itself against gravity, and it does not need protection from terrestrial winds or weather. However, it needs to be protected from certain space hazards such as micro meteors and solar flares.

A 2021 review paper in the Journal of Thermal Energy System titled 'A Review on Space-Based Solar Power' by Shubham S. Gosavi et al. highlights the need for an efficient and lightweight material to create the solar panels of the power system. It mentions that the faculty of Caltech is designing a way to reduce the weight of solar power satellites by using materials that have low density (ultralight materials) and structures, integral circuits, or direct current (D.C.) to radiofrequency (R.F.) power conversion and phase control and devise advanced photovoltaic devices from such materials. The conclusion of the paper explains that space-based solar power could be more prominent and efficient in comparison to conventional energy sources. The primary reason for this is the fact that microwave transmission results in extremely fewer losses in comparison to the currently used traditional options of traditional power transmission. Additionally, such kind of microwave wireless transmission does not cause any harm to the biological ecosystem of earth, and it is a clean source that is capable of meeting sustainable development goals.

A 2021 journal titled 'Space-Based Solar Power: De-risking the Pathway to Net-Zero' clearly lists the risks involved in building the space-based solar power system. These risks have been grouped into the following risks and considerations:

a. Political considerations: Integration with the policies concerning energy; land use for establishing the rectenna sites; the development timescales; integration with the national infrastructure; responsibility and security of operations; international collaboration.

b. **Economic considerations:** The conflict between Levelized Cost of Electricity (LCOE) and other renewable technologies; funding for the system's development; economics of space launch; industrial capabilities.
c. **Social considerations:** Acceptance of the new technology by the public; demonstration of the system and the acceptance of its safety.
d. **Technological considerations:** In-orbit assembly and maintenance; lightweight sandwich panel modules; size and scale of the satellite; efficiency of the wireless power transmission; accuracy of pointing of energy beam and its control; operational life in the space environment.
e. **Legal considerations:** Development of necessary regulations; the United Nations International Telecommunication Union's spectrum allocation for the wireless power transmission; allocation of orbit for the satellite.
f. **Environmental considerations:** Environmental impact on the rectenna site; proving of long-term operational safety and sustainability; creating a strategy for decommissioning and consideration of orbital debris.

III. METHODOLOGY

The collecting satellite would transform solar energy into electrical energy on board, powering a microwave transmitter, and directing its beam toward a collector (rectenna) on the surface of the Earth.
Self-assembling satellites that include reflectors and a microwave power transmitter are launched into orbit. Solar radiation is directed onto solar panels using reflectors or inflated mirrors that cover a large area of space. These solar panels transform solar energy into a microwave or a laser, which they then continuously shoot down to Earth. The beam is captured by power-receiving stations on Earth, where it is added to the electrical system.

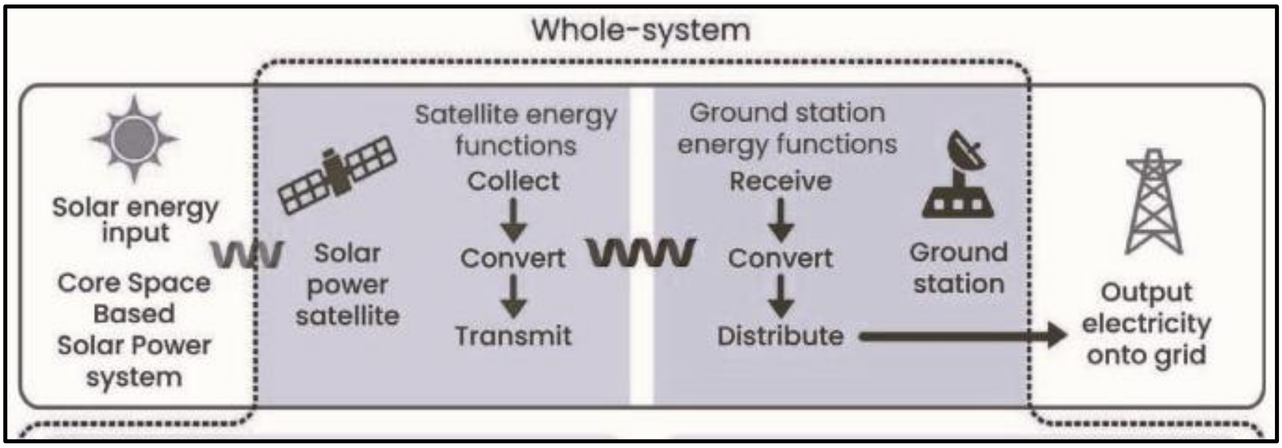

Figure 1: Conceptual overall steps described in the diagram.

a. **Design:**

Three components make up space-based solar power:
- A method of gathering solar energy in space, such as solar concentrators or solar cells
- A method of transferring power to the ground, such as radio waves.
- A method of receiving power on Earth, such as a microwave antenna (rectenna).

b. **Space-based Solar Panels:**

Gallium arsenide-based solar cells have been used for space applications since 1990 because they are more efficient and deteriorate slowly in space than silicon. The most effective solar cells are multi-junction photovoltaic cells, which combine many layers of Indium gallium phosphide, germanium, and gallium arsenide to create more energy. They can approach 47.1% when exposed to intense in the morning 1.5G light and 39.2% when exposed to non-concentrated 1.5G illumination. The cost of launching is decreased by developing ultra-light structures, which is significant in space-based solar generation.

Professors at Caltech who are working on a space-based solar power project have developed an inventive method of reducing the weight of solar power satellites by using low density (ultralight materials) and structures, integral circuits for direct current (DC) to radio frequency (RF) power conversion and phase control, and advanced photovoltaic devices. These solar panels make up the whole power plant and are designed to circle the Earth while remaining almost flat. Single-sided photovoltaic structures that are incredibly lightweight, where solar energy is bombarded by solar concentrators on one face and then transformed into RF power by electronics on the other face.

c. Transmitters:

Power transmission through radio waves is more directed, enabling long-distance power beaming. Shorter wavelengths of electromagnetic radiation generally may be utilized to convert microwave energy back into electricity. Rectenna has achieved an efficiency of greater than 95 per cent. Microwave power beaming has been proposed for transmission from orbit to Earth.

To intensify the beam and transfer the signals to a receiver, the transmitter must be able to convert DC energy power to microwaves. The main obstacle would be to increase the transmitter's efficiency to its maximum level, which would result in very little power loss. The transmitter is essentially an amplifier that receives the beam, subjects the electrons to the cavity, and then creates oscillations in the microwave frequency range based on variations in that range. Amplification equipment, which amplifies the signal and then transforms it to the correct frequency, is part of the transmission antenna itself. The wave dipole is a highly important component in antenna design. Since the dipole length is regarded as being half of a wavelength in this context, where microwave wavelengths are around 30 centimetres, we must maintain the dipole of the antenna between around 12 and 15 centimetres to get greater performance. As seen in Fig. 2, a space-based solar power station must have a perfect transmission antenna that allows for very little loss, as this is the most crucial component for the station's operation. The beam is compressed at a higher frequency. Thus, a receiving array that is of reasonable size can be used to gather microwaves.

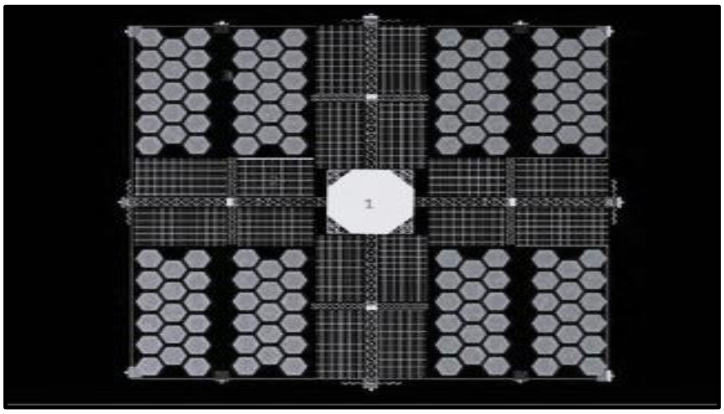

Figure 2: Conceptual prototype of the space-based solar power module

d. Orbital Location:

The fundamental advantage of putting a space power station in a geostationary orbit is that the antenna shape remains constant, making it easier to keep the antennas aligned. Another benefit is that virtually continuous power transmission is available immediately after the first space power station is launched into orbit; other space-based power stations require significantly longer start-up times before they can provide nearly constant power. As a forerunner to GEO space-based solar power, a network of LEO space power plants has been suggested. The Solar Power Satellite energy system concept is to place massive satellites with large arrays of solar cells installed on them in geosynchronous orbit 35,838km above the Earth's surface.

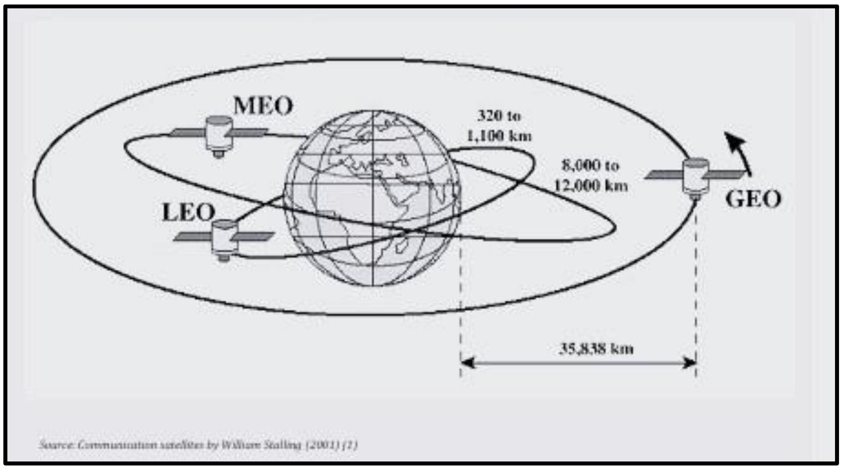

Figure 3: Presentation of LEO, MEO and GEO orbits

e. Rectenna (Earth-Based receiver):

Microwave broadcasts from the satellite would give about 95% efficiency. With a conventional microwave antenna, the reception efficiency is better, but its cost and complexity are high. Rectenna would likely be several spread kilometres across. To catch the microwaves, a rectangular antenna with vast dimensions is needed.

Since the diameter of this antenna should only be a few kilometres, the potential for great energy collection is present. These microwaves are directed to the intended area on Earth by the space-based solar power transmitter antenna. The Rectenna then collects this beam and transforms it into electrical energy, which may then be delivered to a power plant and subsequently made available to end-users. By pointing in the direction of that Rectenna, this antenna's effectiveness would be improved.

IV. CONCLUSION

With space-based solar power, the environmental effects can be reduced while resolving the energy and greenhouse gas emission issues. It may be reasonably presumed that we won't run out of this energy source anytime soon because of space-based solar power's continual large energy output capabilities and the fact that the sun is expected to last for another 10 billion years. Space-based solar power can indeed offer the world clean, dependable power around the clock at a lower cost than any other energy source. The correct political environment, especially leaders who can propel this innovation, is a crucial element in making SBSP a fully independent energy source. Over the next 20 to 30 years, the energy demand will continue to increase. Space solar power is one example of an energy source that might be gradually developed to ensure that when required in ten to twenty years—these possibilities are accessible for large-scale development and deployment.

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