Journal of
Aerospace Engineering & Technology
https://journals.stmjournals.com/joaet

ISSN: 2231-038X (Online)
ISSN: 2348-7887 (Print)
Volume 15, Issue 2, 2025
May–August
DOI (Journal): 10.37591/JoAET

Review JoAET

Towards a Sustainable Future: A Comprehensive Study on Solar Power Satellites

Mahesh A. Tamhane[1,*], Shweta V. Jadhav[1], Megha S. Kumbhar[1]

Abstract

This study explores solar power satellites (SPS) as a promising solution for sustainable energy. Space-based solar power (SPS) offers a revolutionary approach to clean energy by collecting solar energy in space and transmitting it wirelessly to Earth. Unlike terrestrial solar power, SPS can operate continuously, unaffected by weather or nightfall, providing a stable and sustainable energy source. This study explores the core technologies that enable SPS, including advanced photovoltaic systems for efficient solar energy conversion and wireless power transmission techniques, such as microwave and laser-based methods. It also delves into the significant technical and logistical challenges that must be addressed for successful implementation. These include the complexities of launching and assembling large-scale structures in orbit, ensuring durability in the harsh space environment, and developing safe, reliable transmission systems to deliver energy to Earth. Overcoming these obstacles could unlock a transformative global energy solution, helping to meet rising demand while reducing greenhouse gas emissions and reliance on fossil fuels. It also considers the environmental, economic, and geopolitical implications of integrating SPS into global energy systems. Despite existing hurdles, SPS holds significant latent for summit forthcoming energy demands and combating climate change.

Keywords: Solar power satellites (SPS), wireless power transmission, future energy demands

INTRODUCTION

The rising mandate for clean, sustainable energy solutions to fight climate change and encounter worldwide energy requirements has led to a renewed interest in innovative technologies. Among these, Solar Power Satellites (SPS) have emerged as a capable concept with the latent to revolutionize the way we generate and distribute energy. The idea of harvesting solar energy in space, where sunlight is abundant and constant, and transmitting it to Earth through microwave or laser beams, was first proposed in the 1960s by Peter Glaser. Since then, advancements in space technology, photovoltaic cells, and wireless power transmission have reignited interest in SPS as a viable energy solution.

SPS systems could provide a continuous and reliable source of energy, overcoming the limitations of terrestrial solar power, such as intermittency caused by weather patterns and the day-night cycle. These systems also offer the advantage of being able to serve regions with limited access to energy, including remote or disaster-prone areas, by transmitting power across vast distances. However, despite the potential benefits, several challenges remain, including the high cost of launch and deployment, technological complexities in energy transmission, and concerns about the environmental and economic impacts of large-scale space-based energy production. This

*Author for Correspondence
Mahesh A. Tamhane
E-mail: maheshtamhane9@gmail.com

[1]Professor, Department of Electronics and Telecommunication Engineering, Rajgad Dnyanpeeth Technical Campus, Shri Chhatrapati Shivajiraje College of Engineering, Dhangawadi, Pune, Maharashtra, India

Receiving Date: April 15, 2025
Accepted Date: April 24, 2025
Published Date: May 22, 2025

Citation: Mahesh A. Tamhane, Shweta V. Jadhav, Megha S. Kumbhar. Towards a Sustainable Future: A Comprehensive Study on Solar Power Satellites. Journal of Aerospace Engineering & Technology. 2025; 15(2): 1–8p.

© STM Journals 2025. All Rights Reserved

study explores the concept of Solar Power Satellites, providing a wide-ranging analysis of the existing state of research, technological advancements, and the challenges involved in bringing SPS from concept to reality. It also examines the potential environmental, economic, and geopolitical implications of integrating SPS into the global energy grid, contribution perceptions into how this technology could shape the future of sustainable energy [1–3].

LITERATURE REVIEW

Solar Power Satellites (SPS) have garnered significant attention, which envisioned harnessing solar energy from space and transmitting it to Earth. In recent years, advancements in photovoltaic (PV) technology and wireless power transmission (WPT) have renewed interest in SPS.

Technological Advancements

Recent improvements in PV cells, especially multi-junction solar cells, have made SPS more feasible by increasing energy efficiency in space conditions. The work highlights the potential for PV cells to exceed 40% efficiency. Additionally, wireless power transmission technologies, including microwave and laser-based systems, have seen notable advancements, with studies showing promising results in reducing transmission losses.

Deployment and Challenges

One significant challenge is the high cost and complexity of launching and maintaining SPS infrastructure. The substantial expense of building large-scale SPS systems, though innovations in autonomous construction and in-orbit assembly offer potential solutions. The work focuses on improving satellite durability and minimizing space-related damage.

Environmental and Economic Impacts

SPS offers a constant, weather-independent energy source, making it mainly valuable for regions with limited access to reliable power. Environmental concerns, such as the potential effects of microwave transmission on wildlife, have been addressed in studies, signifying that governing measures could mitigate risks. Economically, although primary expenses are high, the long-term benefits, such as stable energy prices and reduced carbon emissions, could outweigh the investment.

Future Directions

Current research is focused on improving energy storage, beamforming techniques, and integrating SPS into existing energy grids. Hybrid systems combining SPS with terrestrial energy sources are being discovered to enhance overall energy resilience.

In summary, while SPS faces significant technical and economic challenges, ongoing research suggests that it could become a crucial part of the future energy landscape, offering sustainable and reliable energy from space.

OBJECTIVES

- *Examine technological advancements:* Review recent progress in solar photovoltaic technology and wireless power transmission for SPS.
- *Evaluate challenges:* Analyze technical, economic, and logistical hurdles in deploying and maintaining SPS systems.
- *Assess environmental and economic impacts:* Investigate the environmental benefits and economic feasibility of SPS.
- *Explore geopolitical implications:* Discuss the potential impact of SPS on global energy markets and access.
- *Identify future research directions:* Highlight key research areas to overcome current challenges and improve SPS technology [1, 4].

© STM Journals 2025. All Rights Reserved

DEMONSTRATED PROJECTS

The *demonstrated projects* related to Solar Power Satellites (SPS) are:

1. *NASA's SPACE Solar Power Initiative (SSPI):* NASA has been exploring SPS through the SSPI, focusing on photovoltaic technology, microwave power transmission, and modular satellite systems. No full-scale deployment yet, but significant progress in key technologies [5].
2. *Japan's Space Solar Power Program:* JAXA has been developing SPS systems, with successful small-scale demonstrations of wireless energy transmission using microwaves. Japan aims for a pilot project in the 2020s and a full-scale system [6].
3. *SPS-ALPHA (Caltech):* A conceptual project by Caltech, SPS-ALPHA focuses on large phased array antennas to transmit power from space. The project addresses critical challenges in energy transmission and satellite assembly [4].
4. *China's SPS Research:* China has demonstrated wireless energy transmission in the form of microwaves and plans to implement a 1 MW SPS system by 2030, with larger systems for the 2040s [7].
5. *UK's Space-Based Solar Power Research:* The UK government is funding feasibility studies for SPS, aiming to develop small-scale demonstrators in the coming decades [8].
6. *ESA's Space Solar Power Demonstrator:* The European Space Agency is conducting studies on space-based solar power and plans future demonstration missions to test key SPS technologies.

These projects show significant progress in SPS development, though full-scale systems are still in the research and demonstration phase [9].

DESIGN REQUIREMENTS OF SPS

The successful deployment and operation of Solar Power Satellites (SPS) require meeting several critical design requirements across various technological domains. These requirements aim to ensure efficient energy collection, transmission, and reception, while also addressing challenges related to cost, sustainability, and system integrity. Figure 1 shows the design of solar power satellite. Below are the key design requirements.

Energy Collection and Conversion

- *High-efficiency solar cells:* Solar panels in space must maximize energy conversion efficiency to compensate for the higher cost and complexity of space missions. Multi-junction photovoltaic (PV) cells, capable of achieving efficiencies over 40%, are ideal for this purpose.

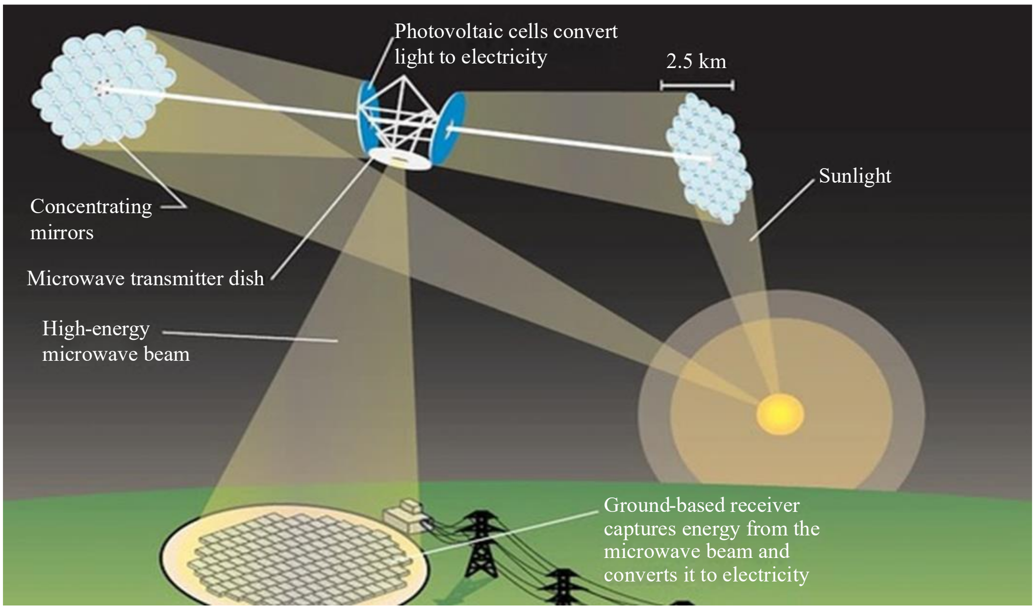

Figure 1. Design of solar power satellite.

© STM Journals 2025. All Rights Reserved

- *Durability and reliability:* Solar cells must withstand harsh space conditions (radiation, temperature variations) without significant degradation over time.
- *Lightweight and flexible design:* The solar arrays should be lightweight and capable of being deployed in orbit, using flexible materials that can be easily packed and assembled.

Power Conversion and Transmission

- *High-efficiency power conversion:* The energy collected by solar panels must be efficiently converted into either microwave or laser beams for transmission to Earth. High efficiency is crucial to minimize energy losses during conversion and transmission.
- *Beamforming and directional control:* The system must accurately focus and direct the energy beam towards the receiver on Earth using advanced beamforming technologies like phased arrays.
- *Low losses in transmission:* The power transmission system (microwave/laser) should minimize energy loss during long-distance travel through space and Earth's atmosphere.

Structural Design and Stability

- *Modular and scalable design:* The SPS should be designed for modular construction in orbit, allowing for scalable systems that can be expanded as energy demands grow.
- *Autonomous assembly:* Given the complexity and cost of space missions, SPS components should be designed for autonomous assembly and maintenance in orbit to reduce reliance on human space missions.
- *Orbital stability and positioning:* The satellite must maintain its position in geostationary orbit or another suitable orbit to ensure continuous solar exposure and power transmission.

Power Reception on Earth

- *Efficient ground receivers:* Ground-based systems need to be designed to efficiently capture and adapt the microwave or laser energy transmitted from space. This requires large, highly sensitive receivers (e.g., rectenna arrays for microwaves).
- *Energy conversion and grid integration:* The system must ensure smooth adaptation of received energy into operational electrical power, integrated seamlessly into existing energy grids or storage systems.

Safety and Environmental Considerations

- *Minimizing health risks:* The microwave or laser transmission should not harm the environment, humans and animals. Shielding and beam power controlling are needed to ensure safety.
- *Impact on space environment:* The satellite design should minimize space debris creation and ensure long-term sustainability in orbit by incorporating self-destruct or deorbiting capabilities at the termination of the satellite's operational life.

Cost and Sustainability

- *Cost-effective launch and deployment:* Given the high cost of launching payloads into space, SPS components must be designed to minimize mass and volume to reduce launch costs.
- *Long-term sustainability:* The SPS system should be capable of long operational lifetimes, with efficient in-orbit servicing capabilities to extend their operational lifespan.
- *Energy storage:* Ground-based energy storage systems may be required to ensure energy supply during periods when direct transmission is not possible (e.g., during adverse weather conditions or eclipses).

Geopolitical and Regulatory Compliance

- *International regulations:* The design must fulfil the international protocols for space activities, including frequency allocation for energy transmission, orbital traffic management, and environmental protection laws.

© STM Journals 2025. All Rights Reserved

- *Alliance with international partners:* Given the scale of SPS systems, alliance with international space agencies and private space companies will be necessary for shared development, launch, and operational costs.

Monitoring and Maintenance
- *Real-time monitoring:* Systems for continuous monitoring of the satellite's health, energy production, and transmission efficiency should be integrated.
- *Automated maintenance:* The satellite design should incorporate autonomous systems for fault detection, correction, and in-orbit repairs to ensure long-term operational stability.

By addressing these design requirements, Solar Power Satellites can evolve from theoretical concepts to practical deployable solutions capable of providing sustainable energy for Earth [7, 9, 10].

CONFIGURATION OF SPS

Solar Power Satellites (SPS) would be positioned in geosynchronous orbit, distinguishing them from current satellites by their ability to produce remotely more power than what is needed for their own operation. These satellites would capture solar energy, convert it into electrical energy, then transform it into microwaves which would be transmitted to Earth, where they would be received by large arrays known as rectifying antennas, or Rectennas, and then converted back into usable electricity.

Each SPS would be enormous, measuring around 10.5 km in length and 5.3 km in width, with an average area of approximately 56 km^2. The satellite's surface would be equipped with about 400 million solar cells. The transmitting antenna on the satellite would span about 1 km in diameter, while the receiving antenna on the Earth's surface would cover approximately 10 km in diameter. To accomplish a highly focused beam, a substantial amount of power must be collected and directed into a large transmitter array.

The power would be transmitted to Earth as microwaves at a frequency of 2.45 GHz. Microwaves are advantageous due to their wider bandwidth, smaller antenna sizes, sharper beam focus, and ability to travel in straight lines. Frequencies between 2 and 3 GHz are ideal for transmitting power from an SPS to a ground-based Rectenna. The amount of power that an SPS could provide to consumers would be about 5 GW. The microwave beam's peak intensity would be 23 mW/cm^2.

SPS systems offer the benefits of ground-based solar power but with the added advantage of functioning effectively in cloudy weather or at night. Essentially, an SPS functions like a solar array by capturing solar energy from space and converting it into electricity, simplifying the satellite's design and reducing its complexity.

MICROWAVE POWER TRANSMISSION

In Solar Power Satellites (SPS), the microwave transmission system involves three main components:
1. Converting the direct power from photovoltaic cells into microwave power on satellites positioned in geosynchronous orbit above Earth.
2. Creating and controlling a microwave beam directed with precision at specific locations on Earth's surface.
3. Collecting the microwave energy and converting it back into electrical power at the Earth's surface.

The key components involved in the Microwave Power Transmission (WPT) system are the transmitter, beam control, and the receiving antenna, known as the Rectenna. At the transmitting end, microwave power tubes, such as magnetrons and klystrons, serve as the radio frequency (RF) power sources. The Rectenna is a crucial component in WPT systems, specifically designed for the purpose of receiving and converting microwave energy. The following section provides a detailed description of each of these components.

© STM Journals 2025. All Rights Reserved

Transmitter

A key requirement of a transmitter is its ability to efficiently convert DC power into RF power and radiate it in a controlled manner with minimal loss. The effectiveness of the transmitter directly impacts the overall competence of the system, along with the thermal management requirement. The key components of the transmitter include the DC-to-RF converter and the transmitting antenna. Power distribution at the transmitting antenna is given by the equation $1/r^2$, where r is the radius of the antenna. There are mainly three types of DC-to-RF power converters: magnetrons, klystrons, and solid-state amplifiers.

Rectenna

The SPS (Space Solar Power) system will require a large reception area featuring a Rectenna array, which will be connected to the existing power grids on Earth. Although each individual Rectenna element only provides a few watts, the collective power received can total in the Gigawatt (GW) range.

A Rectenna is preferred to convert microwave energy into electrical power, and conversion efficiencies of over 95% having been achieved. The term "Rectenna" is derived from combining "rectifying circuit" and "antenna". A Rectenna, or a rectifying antenna, captures transmitted power and converts it into direct current (DC) electricity. This passive component includes a rectifying diode and functions without requiring an external power source. The Rectenna incorporates a low-pass filter between the receiving antenna and the diode to prevent the re-radiation of higher harmonic frequencies, along with an output smoothing filter. In a demonstration setup, the Rectenna consists of six rows of dipole antennas, with each row comprising eight dipoles. Each row connects to a rectifying circuit composed of low-pass filters and a rectifier. The rectifier used is a GA-As Schottky barrier diode, which is impedance-matched to the dipoles via the low-pass filter. The six rectifying diodes are connected to light bulbs, which act as indicators to show power reception and also dissipate the received energy.

The Earth-based Rectenna has a vital role in the original SPS concept (Figure 2). It would be made up of numerous short dipole antennas, connected by diodes. Microwaves transmitted from the SPS would be received by the dipoles with an efficiency of around 85%. While a conventional microwave antenna might have a higher reception efficiency, it is much more expensive and complex, likely making it impractical. The Rectenna could span several kilometers in size. Despite its large area, crops and livestock could be cultivated beneath it, as the thin wires used for supporting the dipoles would minimally reduce sunlight, or alternatively, the Rectenna could be placed over non-arable land. This would keep land use costs relatively low. The efficiency of collection and conversion for this Rectenna is around 25%, but some Rectennas have been tested to achieve efficiencies exceeding 90% [7, 9, 10].

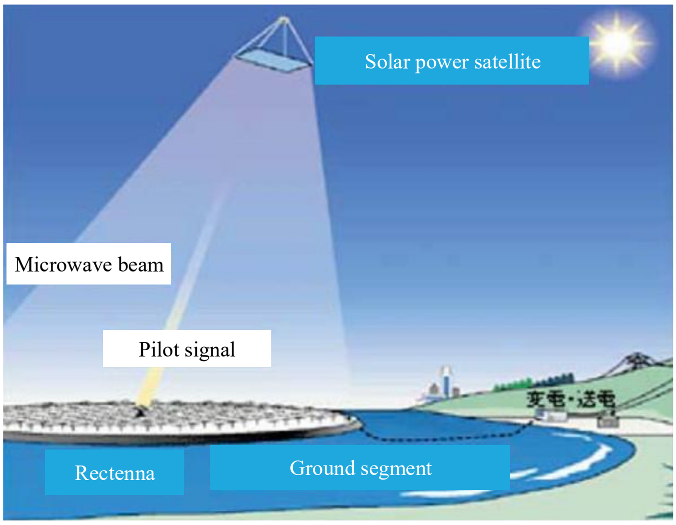

Figure 2. Solar power ground segment.

© STM Journals 2025. All Rights Reserved

KEY FEATURES OF SPS

The perception of Solar Power Satellite is highly appealing due to the numerous advantages that space offers for the solar energy collection. Unlike Earth, space is free from atmospheric interference, meaning the solar collection surfaces would receive a far more intense and consistent amount of sunlight, unaffected by weather conditions. In geostationary orbit, a Space Solar Power (SPS) system would be exposed to sunlight for more than 99% of the time. The only exceptions would occur during a few days around the spring and fall equinoxes, when the SPS might briefly enter Earth's shadow, at most, for 75 min during the night when power demand is typically low. This unique feature of SPS eliminates the necessity for expensive storing systems (such as dams, oil storage, or coal reserves) that are often required in Earth-based power generation setups. Furthermore, SPS would avoid many of the ecological and political challenges related with fossil fuel energy systems [8].

Benefits of Space-Based Solar Power

1. In contrast to oil, gas, ethanol, and coal, space-based solar power generates no greenhouse gas emissions.
2. Unlike bio-ethanol or bio-diesel, space solar power does not compete for valuable agricultural land or rely on fertilizers derived from natural gas. This allows food production to remain a key export rather than being diverted to fuel production.
3. Unlike nuclear energy, space solar power does not create hazardous waste that requires long-term storage and security measures for hundreds of years.
4. Unlike terrestrial solar and wind energy systems, space-based solar power is available around the clock, every day of the year, in vast quantities. It operates independent of cloud cover, daylight, or wind conditions.
5. Unlike nuclear power plants, space-based solar power systems are not vulnerable to terrorist attacks or sabotage.
6. Unlike coal and nuclear energy, space solar power does not rely on environmentally damaging mining operations.
7. Space-based solar power offers the potential for true energy independence for nations that develop it, reducing competition for limited terrestrial energy resources [8, 2].

CONCLUSION

The Space Solar Power (SPS) system is set to be a key development in space and energy technology. However, large-scale retro-directive power transmission and reducing the size and weight of SPS components still require further development. Additionally, advances in space-based construction, transportation, and robotics are needed. Electromagnetic energy, as a man-made extension of the natural electromagnetic spectrum, enhances human life without being a pollutant. From this perspective, SPS is simply a converter that changes visible light into microwaves for efficient energy transmission.

REFERENCES

1. Wood LW, Gilbert AQ. Space-based solar power as a catalyst for space development. Space Policy. 2022 Feb 1; 59: 101451.
2. Glaser PE. An overview of the solar power satellite option. IEEE Trans Microw Theory Tech. 1992 Jun; 40(6): 1230–8.
3. Peters A, Fthenakis VM. Space-based-solar energy: Current status and prospects. In: Energy and Climate Change. Amsterdam: Elsevier; 2025. p. 539–71. doi:10.1016/B978-0-443-21927-6.00003-9.
4. Komerath N, Komerath P. Implications of inter-satellite power beaming using a space power grid. In 2011 IEEE Aerospace Conference. 2011 Mar 5; 1–11.
5. Kulu E, Lofqvist M. Space Solar Power-2023 Survey of Public and Private Initiatives. In74th International Astronautical Congress (IAC 2023). 2023 Oct 2; 1–30.
6. Mori M, Kagawa H, Saito Y. Summary of studies on space solar power systems of Japan Aerospace Exploration Agency (JAXA). Acta Astronaut. 2006 Jul 1; 59(1–5): 132–8.
7. Sasaki S, Tanaka K, Maki KI. Microwave power transmission technologies for solar power satellites. Proc IEEE. 2013 Mar 19; 101(6): 1438–47.

© STM Journals 2025. All Rights Reserved

8. Urdaneta GA, Meyers C, Rogalski L. Solar power satellites: technical challenges and economic feasibility. Future Energy. 2022 Apr 30; 1(2): 09–16.
9. Glaser PE, Maynard O, Mackovciak JJ, Ralph EI. Feasibility study of a satellite solar power station. USA: NASA; 1974 Feb 1.
10. D'Antonio M, Shi C, Wu B, Khaligh A. Design and optimization of a solar power conversion system for space applications. IEEE Trans Ind Appl. 2019 Jan 6; 55(3): 2310–9.

© *STM Journals 2025. All Rights Reserved*