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(Review Article)

Space-based solar power: Unlocking continuous, renewable energy through wireless transmission from space

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Abstract

Space-Based Solar Power (SBSP) is an emerging technology that aims to harness the abundant and uninterrupted solar energy available in space and beam it wirelessly to Earth. This innovative approach addresses the limitations of terrestrial solar energy, such as weather variability and the day-night cycle, by positioning solar power stations in space where sunlight is constant. The stations, composed of large arrays of solar panels, capture the solar energy and convert it into microwaves or laser beams, which are then transmitted to receiving stations on Earth for conversion into usable electricity. Research in SBSP focuses on optimal orbital positions, with geostationary and low Earth orbits being considered for maximum energy capture and efficient transmission. Advancements in materials, wireless power transmission technologies, and space-based assembly techniques are critical to the design and deployment of these stations. Additionally, economic and technical feasibility studies explore the challenges of launching, maintaining, and scaling SBSP systems. These include high initial costs, energy transmission efficiency, safety concerns, and the logistics of long-term maintenance. The potential benefits of SBSP are significant. It offers a clean, renewable energy source that could meet the growing global demand for electricity while reducing reliance on fossil fuels. By providing continuous energy, SBSP could enhance energy security and contribute to global efforts to combat climate change. However, several challenges remain, including addressing space debris risks and ensuring the safety of high-power energy transmission to Earth. As research and technological advancements continue, SBSP holds promise as a transformative solution for future energy needs.

Keywords: SBSP; Wireless energy transmission; Renewable energy; Geostationary orbit; Review

1. Introduction

Space-Based Solar Power (SBSP) refers to the concept of harnessing solar energy in space and transmitting it wirelessly to Earth for use as electricity (Wood and Gilbert, 2022). Unlike terrestrial solar power, which is affected by weather patterns, atmospheric interference, and the day-night cycle, SBSP operates in the vacuum of space, where sunlight is abundant and uninterrupted (Malaviya *et al*., 2022, Ukoba *et al.,* 2024). This allows for the continuous collection of solar energy, making SBSP a potentially transformative solution for meeting global energy demands. The basic premise involves placing large solar power stations in space, equipped with photovoltaic panels that capture solar radiation and convert it into electrical energy (Gosavi *et al*., 2021). This energy is then transmitted to Earth using microwave or laser beams, where it is received by ground stations and converted into usable electricity for homes, industries, and grids. The significance of SBSP lies in its potential to provide a continuous, large-scale supply of renewable energy, overcoming some of the inherent limitations of terrestrial solar power (Cash, 2019). Earth-based solar panels are only functional during daylight hours and are often limited by cloud cover, weather conditions, and geographical constraints. In

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contrast, solar panels in space receive constant sunlight, with no interruptions from atmospheric conditions or the rotation of the Earth (Bermudez-Garcia *et al.*, 2021). This makes SBSP an attractive option for regions with high energy demand but limited access to renewable energy sources. Additionally, as global energy needs continue to rise, SBSP presents an opportunity to reduce dependency on fossil fuels and mitigate the environmental impacts associated with carbon emissions and climate change (Joseph *et al.*, 2022, Oviroh *et al.,* 2023). Currently, there is growing interest and ongoing research into the development of SBSP technologies. Several countries and space agencies are actively exploring the feasibility of building and deploying space-based solar power systems. For instance, NASA has been investigating SBSP since the 1970s and has conducted various studies to understand its potential and challenges. In Japan, the Japan Aerospace Exploration Agency (JAXA) has been working on SBSP technology for several decades and has made significant progress in the design and testing of wireless power transmission systems (Vedda and Jones, 2020). Japan aims to develop a fully operational SBSP system by the 2030s, capable of delivering large amounts of clean energy to Earth. The European Space Agency (ESA) has also expressed interest in SBSP, with its Space-Based Solar Power initiative aimed at assessing the technical and economic viability of such systems (Wilson *et al.*, 2022). Private companies and organizations are also joining the effort to advance SBSP technology. Notably, companies like Northrop Grumman and the China Academy of Space Technology are working on research and development projects to create efficient and cost-effective SBSP systems. These efforts are part of a broader global push to diversify energy sources and invest in innovative technologies that address the urgent need for sustainable energy solutions. Despite the promise of SBSP, several technical, economic, and environmental challenges must be overcome for it to become a viable energy source. The cost of launching and maintaining large-scale solar power stations in space is currently prohibitively high, and the efficiency of wireless power transmission remains a significant technical hurdle (Zhang *et al.*, 2021). Safety concerns related to the beaming of high-power energy from space to Earth must also be addressed to ensure that SBSP does not pose risks to human health, wildlife, or the environment. Nevertheless, advancements in materials science, autonomous space systems, and wireless energy transfer technologies are gradually bringing SBSP closer to reality (Hsu, 2021). Space-Based Solar Power represents a potentially revolutionary shift in how the world generates and consumes energy. By capturing solar energy in space and transmitting it to Earth, SBSP offers a clean, renewable energy source with the potential to provide continuous power without the limitations of terrestrial solar systems. With growing interest from governments, space agencies, and private companies, SBSP could play a crucial role in meeting the world's future energy needs while reducing dependence on fossil fuels and combating climate change (Garretson, 2021). As; Goswami and Garretson, 2022 research and technological advancements continue, SBSP remains an exciting frontier in the quest for sustainable, large-scale energy solutions.

2. Design and Development of Space-Based Solar Power Stations

The design and development of Space-Based Solar Power (SBSP) stations represent a significant technological frontier in renewable energy (Scott *et al.*, 2022). These stations aim to harness solar energy from space and transmit it wirelessly to Earth, providing continuous, large-scale power without the limitations of terrestrial solar systems. The process involves several complex components, including solar panels, wireless energy transmission systems, and receiving stations on Earth. This explores the structure of SBSP stations, the methods of wireless power transmission, and the advancements in materials and engineering that make this vision increasingly feasible.

A typical SBSP station consists of three primary components: solar panels, a wireless energy transmission system, and Earth-based receiving stations (Gosavi *et al.*, 2021). The core component of an SBSP station is its solar panels. These panels are designed to capture solar energy, which is abundant in space, where sunlight is constant and uninterrupted. Space-based solar panels must be more efficient than terrestrial ones, requiring advanced photovoltaic technologies to maximize energy conversion. The large arrays of panels, spanning several kilometres, are positioned to continuously face the sun, optimizing energy collection (Wang *et al.*, 2022). Once energy is collected, it must be transmitted wirelessly to Earth. This involves converting the solar energy into either microwave or laser beams, which are directed toward receiving stations on the planet's surface. These systems require precise control mechanisms to ensure that the energy beam is accurately aimed and consistently focused on the receiver. The final component of the system consists of receiving stations on Earth, which are typically large rectenna arrays (Tierney *et al.*, 2021). Rectennas, or rectifying antennas, convert the transmitted microwaves or laser beams back into electricity. These stations must be strategically located to optimize energy reception and ensure minimal energy loss during the transmission process.

In this approach, the solar energy collected by the SBSP station is converted into microwaves and beamed down to Earth using antennas. Microwaves are favoured due to their relatively low energy loss during transmission through the atmosphere (Jakhar *et al.*, 2020). The receiving station, equipped with rectennas, captures the microwave beams and converts them back into electrical power. Microwave transmission is the most developed and studied method, as it poses fewer challenges in terms of atmospheric interference. Another potential method involves converting solar energy into laser beams, which are then transmitted to Earth (Sun *et al.*, 2022). Lasers can deliver highly focused energy, but they are more susceptible to atmospheric disturbances like cloud cover, which can reduce the efficiency of energy transmission. Additionally, safety concerns arise with laser transmission, as high-intensity beams can pose risks to aircraft, satellites, and human health if not properly managed. Both methods of wireless transmission face several challenges. Atmospheric interference, such as clouds and weather conditions, can affect the efficiency of energy transfer, particularly for laser transmission. Efficiency is another key issue, as current technologies struggle to achieve optimal energy conversion rates (Ahmed *et al*., 2020). Finally, there are safety concerns associated with transmitting large amounts of energy wirelessly. Ensuring that energy beams do not interfere with satellites, aircraft, or human populations is a critical consideration in the design of SBSP systems.

The development of SBSP stations relies heavily on advancements in materials and space engineering (Medin, 2021). The harsh environment of space necessitates the use of lightweight, durable materials capable of withstanding extreme temperatures, radiation, and micrometeoroid impacts. Advanced materials such as carbon-fibre-reinforced polymers, lightweight composites, and radiation-resistant coatings are being developed to ensure the longevity and efficiency of SBSP systems. The enormous size of space-based solar panels means that minimizing weight is crucial to reducing launch costs and ensuring structural integrity. New materials that combine strength and flexibility are being designed to create large, deployable solar arrays that can be transported to space in compact forms and then expanded once in orbit (Ma *et al*., 2022). Another key innovation is the use of autonomous systems for the deployment and assembly of SBSP stations. Given the scale of these stations, human-led assembly would be impractical and dangerous. Instead, robotic systems and self-assembling structures are being developed to autonomously deploy solar panels and other components once the station reaches orbit. These autonomous technologies are crucial for reducing operational costs and ensuring the scalability of SBSP stations. Additionally, satellite servicing and maintenance will play an essential role in the long-term viability of SBSP systems. Robotic repair systems and modular designs are being explored to allow for the replacement of faulty components without the need for costly missions or complete station overhauls (Nordin *et al*., 2022).

The design and development of space-based solar power stations represent a significant advancement in the pursuit of sustainable energy solutions (Dotson *et al*., 2022). By leveraging continuous solar energy in space and using innovative wireless transmission technologies, SBSP stations have the potential to provide a constant and reliable source of renewable energy to Earth. However, significant challenges remain, including efficiency improvements in energy transmission, ensuring safety, and overcoming the high costs associated with space operations. Advances in materials and engineering, particularly in lightweight structures and autonomous assembly systems, are bringing the dream of SBSP closer to reality (McElfresh *et al*., 2020). As research and technology development continue, SBSP could become a transformative solution for meeting the world's growing energy needs while reducing dependence on fossil fuels.

2.1. Orbital Positions and Configurations for Maximizing Energy Collection in Space-Based Solar Power (SBSP) Stations

Space-Based Solar Power (SBSP) stations are designed to capture solar energy in space and transmit it wirelessly to Earth, offering a continuous and renewable energy source as illustrated in Figure 1 (Snead, 2019; Bhagat and Joy, 2021).

The efficiency of these systems largely depends on the orbital positions and configurations of the solar power stations. By selecting the best orbital locations and optimizing solar panel alignments, SBSP systems can maximize energy collection and minimize transmission losses. This explores the best orbital locations for SBSP stations, strategies for maximizing energy collection, and considerations for energy transmission pathways.

Choosing the optimal orbit for SBSP stations is crucial for ensuring continuous solar energy collection and efficient transmission to Earth (Venugopal *et al*., 2022). Two primary orbital locations are considered for SBSP stations: geostationary orbit (GEO) and low Earth orbit (LEO). Geostationary Orbit (GEO) is an orbital position approximately 35,786 kilometres above the Earth's equator, where a satellite orbits at the same rate as the Earth's rotation. This allows the satellite to remain fixed over a specific point on the Earth's surface. For SBSP stations, GEO offers the advantage of constant visibility to a specific ground-based receiving station, enabling continuous energy transmission. Moreover, GEO provides uninterrupted exposure to sunlight for most of the year, with only minimal eclipses during the equinoxes (Chen *et al*., 2020). However, the high altitude of GEO also presents challenges, including increased costs for launching and maintaining stations, as well as potential signal latency during energy transmission. Low Earth Orbit (LEO), ranges from about 160 to 2,000 kilometers above the Earth's surface. SBSP stations in LEO can benefit from lower launch costs and shorter transmission distances, potentially reducing energy losses. However, LEO stations experience rapid orbital motion relative to the Earth, leading to frequent transitions between sunlight and the Earth's shadow, which interrupts energy collection. Additionally, LEO stations require a network of satellites, or a constellation, to ensure continuous energy delivery to a specific location on Earth, as individual satellites quickly move out of range of ground-based receivers (Ge *et al*., 2022; Darwish *et al*., 2022). Pros and Cons of Orbital Configurations. Continuous coverage over a fixed Earth location, stable sunlight exposure, and fewer satellites are needed. High altitude leads to longer transmission distances, higher costs, and increased signal latency. Lower launch costs, shorter transmission distances, and potentially lower energy losses. Intermittent solar exposure, the need for a satellite constellation, and more complex energy transmission management.

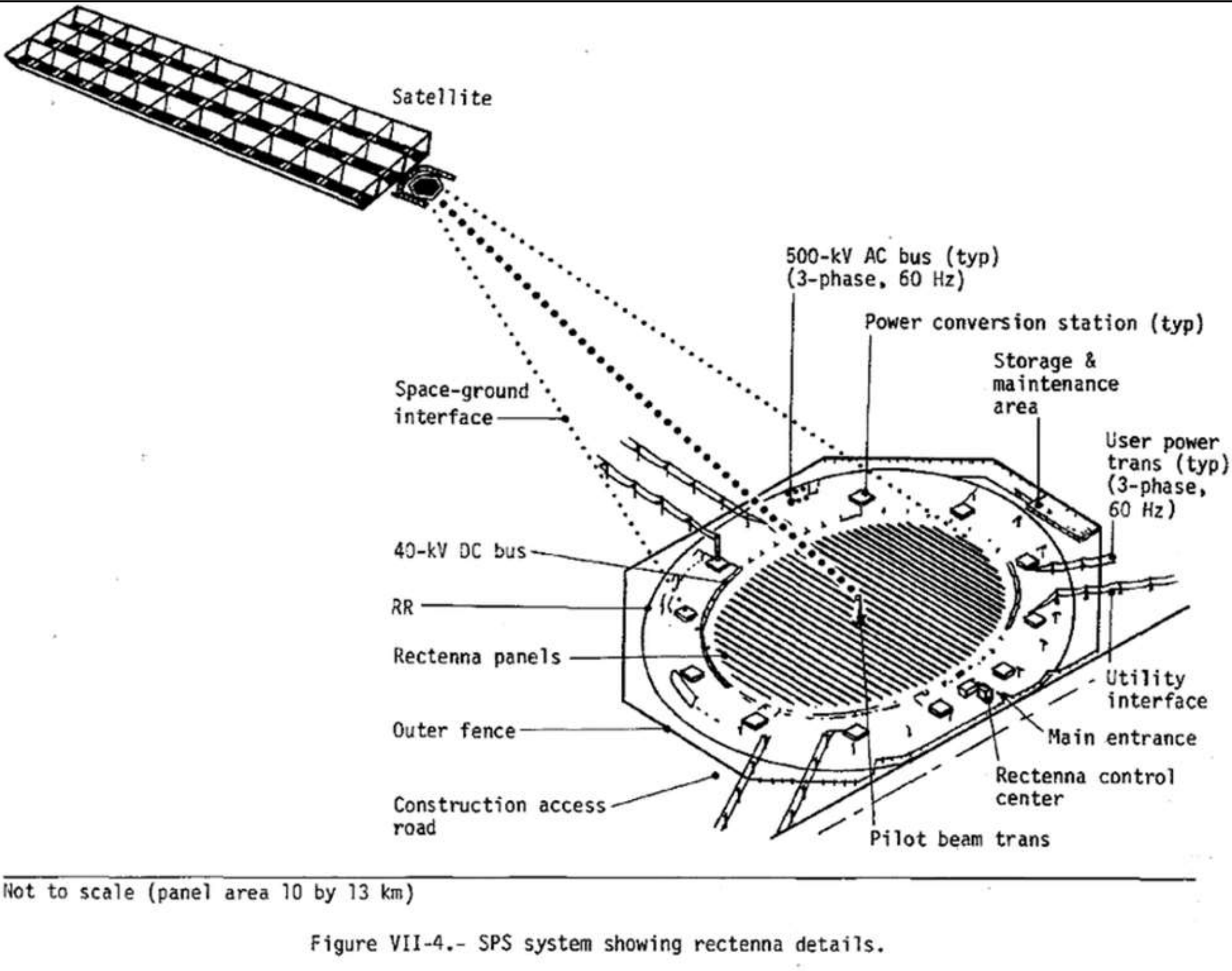

Figure 1 GEO space solar power system (Snead, 2019)

Maximizing energy collection in SBSP stations involves ensuring continuous exposure to sunlight and optimizing solar panel configurations and alignments for peak efficiency (Lumbreras and Pérez Grande, 2021). One of the primary advantages of SBSP is the ability to collect solar energy without the interruptions caused by the Earth's atmosphere or the day-night cycle. In GEO, SBSP stations can remain in almost constant sunlight, with only brief periods of eclipse during the equinoxes. In contrast, LEO stations experience more frequent transitions between sunlight and shadow, reducing the overall energy collection time (Prol *et al*., 2022). To maximize energy collection, SBSP stations must be placed in orbits that provide the longest possible exposure to sunlight. The efficiency of energy collection also depends on the configuration and alignment of solar panels. Panels should be designed to track the Sun's position continuously, adjusting their orientation to maximize the incident sunlight on their surface (Rajan and Ramachandran, 2021). In GEO, panels can maintain a relatively stable orientation, requiring minimal adjustments. In LEO, however, the rapid motion of the satellite requires more dynamic adjustments to ensure optimal sunlight exposure. Advanced tracking systems and adaptive panel designs are essential for maintaining peak efficiency in energy collection.

Effective energy transmission from SBSP stations to Earth requires strategic placement of stations to minimize transmission distance and energy loss (Alogla *et al*., 2021, Agupugo *et al*., 2024). Additionally, identifying suitable Earth-based locations for receiving stations is crucial for ensuring efficient energy transfer. The distance between the SBSP station and the Earth's surface plays a significant role in determining the efficiency of energy transmission. Longer distances, such as those from GEO, can lead to greater energy loss due to signal dispersion and atmospheric attenuation.

Conversely, shorter distances from LEO can reduce energy loss, but the rapid movement of LEO satellites complicates consistent energy delivery. A balance must be struck between orbit altitude and transmission efficiency to optimize energy delivery. The placement of ground-based receiving stations, or rectennas, is critical for the successful operation of SBSP systems (Sudhakar, 2020). These stations must be located in areas with minimal atmospheric interference, such as regions with low cloud cover and stable weather conditions. Additionally, receiving stations should be situated away from densely populated areas to minimize potential safety risks associated with high-power energy transmission. Remote or semi-remote locations are often ideal for receiving stations, offering both operational efficiency and safety.

The design and operation of SBSP stations are highly dependent on their orbital positions and configurations. Geostationary orbits offer continuous energy collection and stable transmission pathways but at a higher cost and with greater transmission distances (Matricciani, 2020). Low Earth orbits provide shorter transmission distances and lower costs but require complex constellations to maintain consistent energy delivery. Maximizing energy collection involves ensuring continuous sunlight exposure and optimizing solar panel alignments, while strategic placement of SBSP stations and ground-based receiving stations is essential for minimizing energy loss during transmission. As research and technology continue to advance, these considerations will play a critical role in the successful deployment and operation of SBSP systems, offering a promising solution for meeting global energy needs.

2.2. Economic and Technical Feasibility Studies of Space-Based Solar Power (SBSP)

The concept of Space-Based Solar Power (SBSP) presents a revolutionary method of harnessing renewable energy by collecting solar power in space and transmitting it to Earth as explained in Figure 2 (Arya *et al*., 2016; Medin, 2021). Despite its immense potential, significant economic and technical feasibility studies are necessary to understand the viability of SBSP on a global scale. This examines the financial considerations of developing and deploying SBSP systems, explores the technological challenges that must be overcome, outlines strategies for maintenance and longevity, and addresses the environmental and safety concerns associated with these systems. The development and deployment of SBSP systems involve substantial financial investments across multiple domains, including launch costs, materials, satellite production, and infrastructure development as explained in Table 1 (Wilson *et al*., 2020; Jones and Nesterova, 2021). The cost of launching materials into space is one of the most significant financial hurdles for SBSP systems. Current launch costs range between $2,000 to $10,000 per kilogram, depending on the type of rocket used and the destination orbit. A fully functional SBSP station would require the transportation of solar panels, transmitters, and structural components, totalling several thousand metric tons. While advancements in reusable rockets, such as SpaceX's Falcon 9, have reduced costs, the scale of an SBSP project still presents a significant financial challenge (Miraux *et al*., 2022). The materials used for SBSP stations must be lightweight, durable, and capable of withstanding the harsh environment of space. Developing advanced materials, such as radiation-resistant composites and lightweight alloys, increases production costs. Additionally, the mass production of specialized satellites designed for energy collection and transmission further adds to the overall financial burden. Ground-based infrastructure, such as large rectennas (rectifying antennas) to receive transmitted energy, must be constructed to support SBSP systems. These receiving stations, which convert microwave or laser beams back into usable electricity, require vast amounts of land and specialized technologies, leading to significant costs for site preparation, equipment, and installation.

Table 1 Key economic and technical factors impacting the feasibility of SBSP (Wilson *et al*., 2020)

Aspect	Key Factors	Challenges	Current Developments	Potential Solutions
Economic Feasibility				
Capital Investment	High initial costs due to space infrastructure	Launch costs, satellite development, and installation	Cost reduction in reusable rockets (e.g., SpaceX)	Economies of scale and government-private partnerships
Operational Costs	Long-term maintenance and operational expenses	Space repairs, monitoring systems, and satellite lifespan	Long-term cost-saving due to autonomous systems	Developing automated maintenance systems
Return on Investment (ROI)	ROI over long-time horizons	Long payback periods; high initial outlay	High energy demand driving future returns	Government incentives and subsidies to support investment

Market Competition	Competing with terrestrial solar and nuclear power	Cost competitiveness with other renewable sources	Ongoing research on energy pricing and cost efficiency	Innovation in transmission technology (e.g., microwave power)
Technical Feasibility				
Energy Conversion Efficiency	Solar energy conversion to electrical power	High energy losses in space transmission	Development of advanced photovoltaic (PV) and solar arrays	Modular satellite designs, 3D printing in space
Satellite Durability	Longevity of satellites in harsh space environments	Exposure to radiation, micrometeoroid damage	Research in radiation-resistant materials	Enhancing protective shielding for satellites
Energy Storage & Distribution	Storage solutions for continuous energy availability	Limited storage technology, transmission during night	Innovations in high-capacity batteries and superconductors	Developing large-scale space storage systems, improving ground receivers

The success of SBSP systems depends on overcoming several technological challenges related to energy conversion, transmission accuracy, and cooling systems for space operations (El-Shawa *et al*., 2022). One of the key challenges in SBSP systems is optimizing the efficiency of energy conversion. Solar energy must be converted into microwaves or lasers, transmitted to Earth, and then reconverted into electricity. Each stage of this process introduces energy losses, particularly during the conversion and transmission phases. Current energy conversion technologies have relatively low efficiency, and improving these systems is critical to making SBSP economically viable. Wireless power transmission relies on precisely targeting the energy beams to ground-based receiving stations (Rodenbeck *et al*., 2021). This requires highly accurate control systems to ensure that energy beams remain focused on the rectennas, even as satellites move in their orbits. Any misalignment could result in energy losses or potential hazards to surrounding areas. Developing robust targeting and beam-steering technologies is crucial for ensuring efficient energy transfer. The extreme heat generated by solar panels in space, combined with the absence of an atmosphere to dissipate heat, presents a unique challenge for SBSP stations. Effective cooling systems must be developed to prevent overheating of components and ensure the longevity of the station. Advanced thermal control materials and systems, such as radiators and heat-dissipating coatings, are necessary to manage the thermal environment in space (Tachikawa *et al*., 2022).

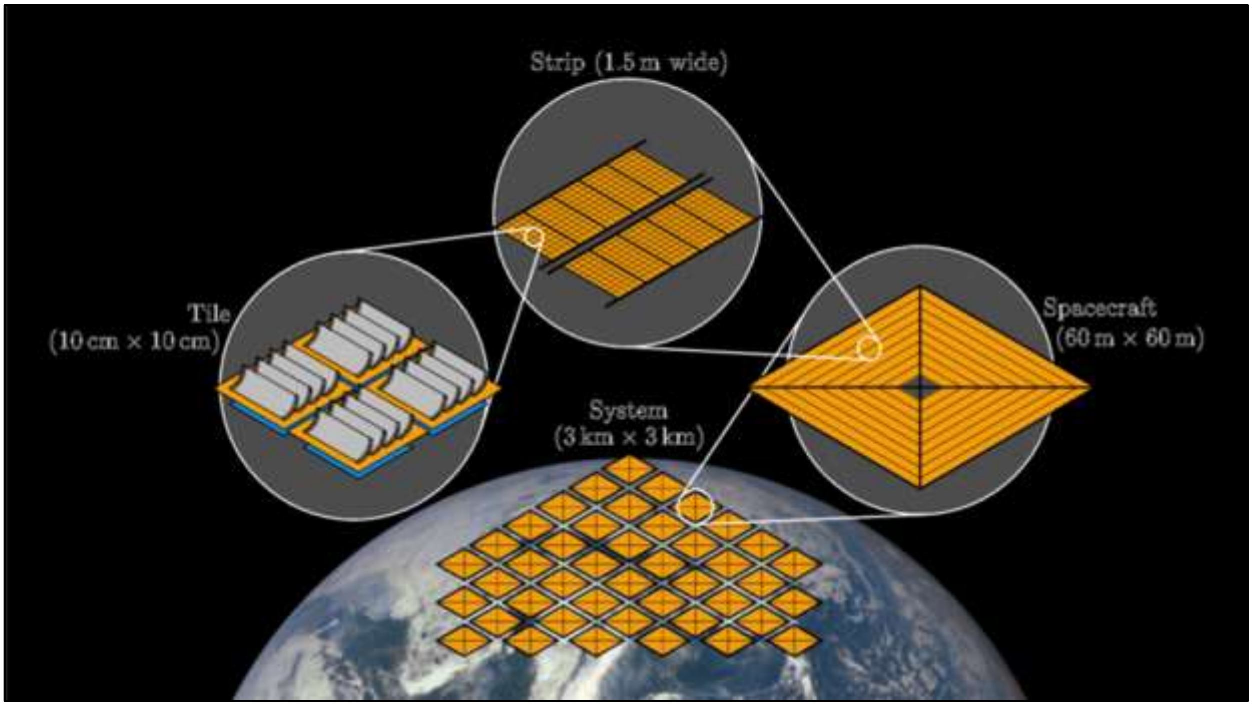

Figure 2 Overview of Space Solar Power System (Arya *et al*., 2016)

The long-term sustainability of SBSP systems depends on effective maintenance strategies and the ability to repair or replace components autonomously. SBSP stations are designed to operate continuously for several decades, making routine maintenance essential (Wilson *et al*., 2020). However, the distance and expense associated with human missions to repair satellites make traditional maintenance approaches impractical. Autonomous systems, capable of detecting and addressing faults in real-time, are therefore necessary for maintaining system functionality. To minimize downtime and ensure continuous energy collection and transmission, SBSP stations must incorporate autonomous repair systems. These systems could include robotic arms or drones designed to repair damaged components or replace faulty solar panels. Modular designs, where individual components can be swapped out without requiring a full system overhaul, can also enhance the longevity of SBSP stations (Coto *et al*., 2021).

The deployment of SBSP systems also raises environmental and safety concerns, particularly related to wireless energy transmission and space debris. Wireless energy transmission, whether through microwaves or laser beams, has the potential to interact with the Earth's atmosphere and ecosystems (Eteng *et al*., 2021). Microwaves, for instance, could cause atmospheric heating, affecting local weather patterns if not properly managed. There is also concern about the potential impact of energy beams on birds, aircraft, and other wildlife that may enter the transmission path. Comprehensive environmental impact assessments must be conducted to evaluate and mitigate these risks. The growing issue of space debris poses a significant threat to SBSP systems. Collisions with debris can damage solar panels, disrupt energy transmission, or even result in complete system failure (Adushkin *et al*., 2020). Additionally, accidents during the launch or operation of SBSP systems, such as misaligned energy beams or structural failures, could pose risks to people and infrastructure on Earth. Strategies to address these risks include developing better debris-tracking systems, incorporating shielding for critical components, and designing fail-safe mechanisms to prevent accidental energy transmission to unintended locations. The economic and technical feasibility of Space-Based Solar Power (SBSP) systems depends on addressing several key challenges. The cost of development and deployment remains a major hurdle, with significant expenses tied to launch costs, materials, satellite production, and infrastructure development. Technological advancements in energy conversion, beam targeting, and cooling systems are essential for ensuring efficient and reliable operation. Maintenance and longevity can be supported by autonomous repair and replacement systems that minimize downtime (Achouch *et al*., 2022). Finally, addressing environmental and safety concerns, such as the impact of wireless energy transmission and the risks posed by space debris, is critical for the safe and sustainable operation of SBSP systems. As research continues and technology advances, SBSP holds the potential to revolutionize the global energy landscape, providing a renewable and continuous power source for the future.

2.3. Economic and Environmental Benefits of Space-Based Solar Power (SBSP)

Space-Based Solar Power (SBSP) represents a groundbreaking technology with the potential to revolutionize global energy supply (Çırak and Pınar, 2021). By capturing solar energy in space and transmitting it wirelessly to Earth, SBSP offers a renewable energy source that can operate continuously, free from the limitations of terrestrial solar power as illustrated in Figure 3 (Gosavi *et al*., 2021). In addition to its technical appeal, SBSP offers significant economic and environmental benefits. This explores the potential for SBSP to transform the global energy market, its role in reducing carbon emissions, and its scalability to serve both developed and developing regions with clean, renewable energy.

The deployment of SBSP systems could have a profound impact on the global energy supply, enhancing energy security and offering economic incentives for investment in space-based energy production. SBSP has the potential to provide a continuous, large-scale supply of clean energy, independent of weather conditions or geographic limitations (Kerscher and Arboleya, 2022). Unlike terrestrial solar power, which is subject to fluctuations in sunlight due to weather and the day-night cycle, SBSP stations positioned in space can collect solar energy 24 hours a day. This continuous energy supply could significantly enhance global energy security, reducing reliance on fossil fuels and minimizing exposure to the volatility of global energy markets. Additionally, SBSP could help stabilize energy prices by providing a reliable and predictable source of energy, reducing the need for costly and environmentally damaging peak-load power plants (Dost, 2020). SBSP offers significant economic incentives for investment, particularly in the long term. While the initial costs of developing and deploying SBSP systems are high, the potential for continuous energy generation presents a lucrative opportunity for investors. Governments and private enterprises could see substantial returns on investment, especially as the demand for renewable energy grows and global efforts to reduce carbon emissions intensify. Furthermore, as space technology continues to advance and the cost of launching satellites decreases, the financial barriers to SBSP deployment may lessen, making it an increasingly attractive option for energy production (Dakora *et al*., 2020). The development of SBSP could also spur growth in the aerospace and satellite industries, creating new jobs and driving innovation.

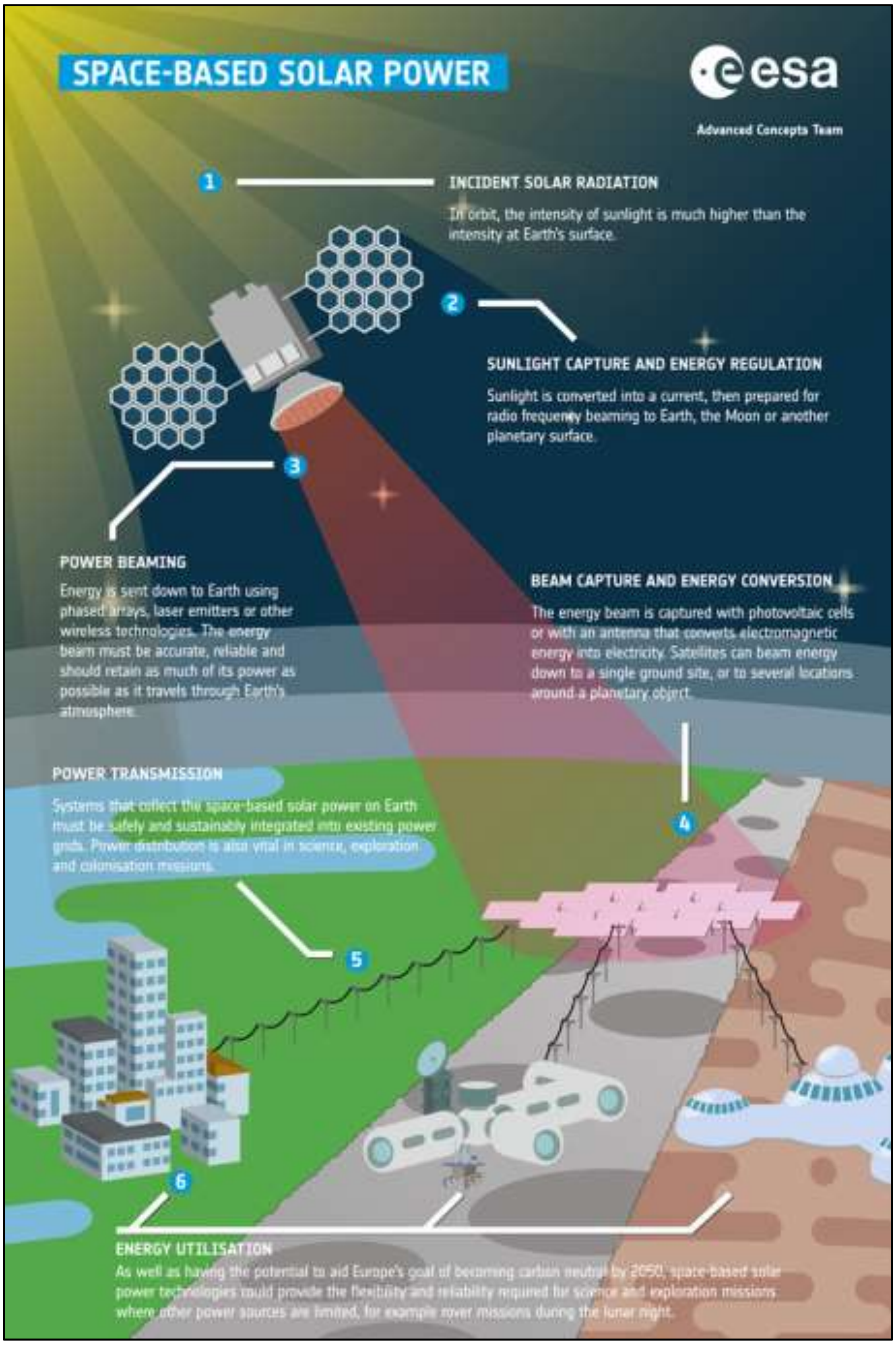

Figure 3 The process of harnessing solar energy from space (Gosavi *et al.*, 2021)

SBSP's contribution to global renewable energy goals and its ability to reduce dependence on fossil fuels are among its most significant environmental benefits (Al-tabatabaie *et al.*, 2022). SBSP has the potential to play a key role in meeting global renewable energy targets. Many countries have set ambitious goals to transition to renewable energy sources in response to the growing threat of climate change. SBSP could provide a large-scale, continuous source of renewable energy that complements existing technologies such as wind, solar, and hydropower. By supplementing terrestrial renewable energy sources, SBSP could accelerate the transition to a low-carbon energy future and help countries meet their commitments under international agreements such as the Paris Agreement. One of the primary environmental benefits of SBSP is its ability to reduce dependence on fossil fuels. The burning of fossil fuels for energy is a major contributor to global greenhouse gas emissions, which are driving climate change (Siddik *et al.*, 2021). SBSP offers a cleaner, more sustainable alternative to fossil fuel-based power generation, with the potential to significantly reduce global carbon emissions. As SBSP systems become more widely adopted, they could displace fossil fuel power plants, leading to substantial reductions in air pollution and greenhouse gas emissions. This shift would not only benefit the environment but also improve public health by reducing the harmful pollutants associated with burning fossil fuels.

SBSP's scalability and its potential to provide clean, renewable energy to both developed and developing regions make it a promising solution for addressing global energy inequality. One of the key advantages of SBSP is its scalability. SBSP systems can be designed to generate vast amounts of energy, and additional stations can be launched over time to meet growing energy demand (Wallach, 2021). Unlike terrestrial power plants, which are constrained by land availability, water resources, and proximity to population centres, SBSP stations can be placed in space, where there are no such limitations. This makes SBSP an ideal solution for meeting the world's long-term energy needs. Moreover, as technology advances and costs decrease, SBSP systems could become more affordable and accessible, enabling large-scale deployment. SBSP's ability to transmit energy wirelessly means it has the potential to serve regions that are currently underserved by traditional energy infrastructure. In many developing countries, access to reliable electricity remains a challenge, with millions of people still lacking access to modern energy services (Amir and Khan, 2022). SBSP could help bridge this gap by providing a clean, renewable energy source that can be distributed globally. By strategically placing ground-based receiving stations in both developed and developing regions, SBSP could supply electricity to areas that currently rely on expensive and environmentally harmful fossil fuel generators. This would not only improve energy access but also support economic development and improve the quality of life in these regions.

Space-Based Solar Power offers a transformative opportunity to address both economic and environmental challenges associated with global energy supply (Black *et al*., 2022). Economically, SBSP has the potential to stabilize energy markets, enhance energy security, and provide attractive returns on investment. Environmentally, SBSP can contribute to reducing the world's carbon footprint by providing a large-scale, continuous source of renewable energy, thereby helping to meet global climate goals. Furthermore, SBSP's scalability and ability to serve both developed and developing regions make it a promising solution for addressing global energy inequality. As research and development continue, SBSP has the potential to become a key pillar of the global energy landscape, driving a cleaner, more sustainable future for all.

3. Conclusion

Space-Based Solar Power (SBSP) holds remarkable potential for transforming global energy production and advancing sustainability goals. The vision for the widespread adoption and commercialization of SBSP envisions a future where space-based solar stations provide a continuous and reliable source of renewable energy, free from the constraints of terrestrial power sources. As technology advances and costs decrease, SBSP could become a cornerstone of the global energy landscape, offering clean energy around the clock regardless of geographical or atmospheric limitations.

However, several significant challenges remain to be addressed before SBSP can become a practical and economically viable solution. Technical barriers include improving energy conversion efficiency, developing precise beam-targeting technologies, and creating effective cooling systems for space operations. Additionally, the high costs associated with launching and maintaining SBSP infrastructure pose substantial economic hurdles. Overcoming these challenges will require sustained research and development efforts, as well as international collaboration to share knowledge, resources, and investment.

The impact of SBSP on the future of energy could be transformative. By providing a constant, large-scale source of renewable energy, SBSP has the potential to revolutionize global energy production, reduce dependence on fossil fuels, and significantly decrease greenhouse gas emissions. Its scalability and ability to deliver energy to both developed and developing regions can address global energy inequality and support economic development. As the world grapples with the pressing need for sustainable energy solutions, SBSP represents a promising avenue for achieving a cleaner, more resilient energy future.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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