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SPACE-BASED SOLAR POWER: SCIENCE FICTION OR A NEAR-FUTURE REALITY

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Abstract. *The global energy demand is experiencing a rapid increase, with projections suggesting a potential doubling or 50% growth in the coming years. In response, the exploration of alternative power generation methods has become imperative. Photovoltaic power plants, while harnessing clean energy from the sun, face limitations due to their reliance on weather conditions and extensive land requirements. Space-based solar power offers a compelling alternative, providing the capability to deliver continuous, carbon-free electricity with a power density exceeding that of terrestrial alternatives by more than tenfold while necessitating significantly less land.*

Space-based solar power systems operate by collecting and converting solar energy in space, which is then transmitted wirelessly to Earth using microwaves or lasers to generate electricity. However, achieving this potential requires overcoming substantial technological challenges, particularly in the domain of wireless power transmission over long distances to effectively reach ground-based receivers.

As the drive towards net-zero emissions intensifies, Space-based solar power is increasingly recognized as a viable option. This paper offers an overview of Space-based solar power as an integrated system. It introduces cutting-edge advancements, including system properties and modern Space-based solar power concept architectures, and examines their applications and spillover effects across various sectors. Additionally, the paper addresses the challenges and risks associated with Space-based solar power, emphasizing key barriers to successful implementation. Despite the availability of much of the requisite technology, its efficiency remains insufficient for practical deployment. Nevertheless, with the participation of private enterprises in the space race and ongoing advancements in system efficiency, the overall costs of Space-based solar power are decreasing. With continued progress and sustained investment, Space-based solar power, in conjunction with other renewable technologies, holds the potential to significantly contribute to cross-sector decarbonization. Ref. 68. Fig. 9.

Keywords: *space-based solar power, solar power satellites, sustainable energy, solar power plant, photo-voltaic plant, solar energy.*

СОНЯЧНА ЕНЕРГІЯ З КОСМОСУ: НАУКОВА ФАНТАСТИКА ЧИ РЕАЛЬНІСТЬ НАЙБЛИЖЧОГО МАЙБУТНЬОГО

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Анотація. *Світовий попит на енергію стрімко зростає, і прогнози вказують на його потенційне подвоєння або зростання на 50 % найближчими роками. З огляду на це зростає потреба в дослідженні альтернативних методів виробництва енергії. Фотоелектричні станції, хоча й використовують чисту енергію Сонця, мають обмеження через залежність від погодних умов та потребу у великих площах*

землі. Космічна сонячна енергія видається привабливою альтернативою, забезпечуючи можливість безперервного постачання безвуглецевої електроенергії з густиною потужності, що перевищує наземні аналоги більш ніж у десять разів, при цьому потребуючи значно менше земельної площі.
Системи космічної сонячної енергії працюють за принципом збирання та перетворення сонячної енергії в космосі, яка потім передається бездротовим шляхом на Землю за допомогою мікрохвиль або лазерів для генерації електроенергії. Проте для реалізації цього потенціалу необхідно подолати значні технологічні виклики, зокрема у сфері бездротової передачі енергії на великі відстані для ефективного досягнення наземних приймачів.
Зважаючи на посилення прагнення до досягнення нульових викидів CO_2, космічна сонячна енергія дедалі більше визнається як реалістичний варіант. У цій статті надано загальний огляд космічної сонячної енергії як інтегрованої системи. Розглядаються новітні досягнення, включно з властивостями систем та сучасними архітектурними концепціями космічної сонячної енергії, а також аналізується їх застосування і вплив на різні сектори. Крім того, у статті висвітлено виклики та ризики, пов'язані з космічною сонячною енергією, з акцентом на ключові бар'єри, що перешкоджають її успішному впровадженню. Попри наявність багатьох необхідних технологій, їхня ефективність поки що недостатня для практичного використання. Проте із залученням приватних підприємств до космічних перегонів та постійним удосконаленням системної ефективності, загальні витрати на космічну сонячну енергію зменшуються. За умови продовження прогресу та постійних інвестицій, космічна сонячна енергія, у поєднанні з іншими відновлюваними джерелами енергії, має потенціал значно сприяти декарбонізації різних секторів економіки країн. Бібл. 68. Рис. 9.

Ключові слова: *космічна сонячна енергія, супутники сонячної енергії, стійка енергетика, сонячна електростанція, фотоелектрична станція, сонячна енергія.*

List of used designations and abbreviations:

SBSP – space-based solar power
AM – air mass
PV – photovoltaic
HCPV – High Concentration Photovoltaics
GEO – Geostationary Earth Orbit
LEO – Low Earth Orbit
MEO – Medium Earth Orbit
LCOE – Levelized Cost of Energy
SD – solar dynamic
RF – radio frequency

Introduction. Global energy consumption is projected to double or increase by 50% over the next 30 years [1]. This surge in demand places significant strain on land and resources, compounding the impact of climate change [2]. The pressing need for clean, sustainable, scalable, and secure energy solutions is more critical than ever.

The acceleration of pollution growth is unprecedented, driven largely by the reliance on coal, natural gas, and oil for energy production [3]. Traditional energy generation methods are associated with the emission of harmful substances, including acid gases, mercury, non-mercury toxins, and organic air pollutants. Power plants alone contribute approximately 10 billion tons of CO_2 to the atmosphere annually [4].

Estimates suggest that by 2050, the global population could exceed 10 billion, with over 85% residing in developing countries [5]. This raises a critical question: How can we meet the increasing energy demands of humanity without causing further environmental harm? Relying on fossil fuels is not a viable solution, as the combustion of coal, oil, and gas releases carbon dioxide, exacerbating global climate change (Fig. 1).

Additionally, current fossil fuel reserves are finite. While nuclear energy mitigates greenhouse gas emissions, it presents challenges related to nuclear waste disposal.

The generation of renewable energy must become a top priority as we strive toward a sustainable society [7]. The sun represents the primary source of energy within our solar system. However, approximately 70% of the solar energy that reaches the Earth's surface is lost due to the day-night cycle and inefficiencies in energy utilization [8].

Current solar cell technologies exhibit a range of efficiencies: the most advanced cells achieve just over 40% efficiency, while more commonly used solar cells typically range between 22% and 27% [7].

Thus, energy storage solutions are required, increasing both the cost and complexity of these technologies. An alternative approach involves using a network of solar-powered satellites in low Earth orbit. This system could deliver continuous power to any location, as at least one satellite would always be in a position to receive sunlight. The concept of solar power satellites (SPS) harnesses solar energy in space to provide a steady supply of electricity on Earth.

In the context of the global need for a sustainable and waste-free energy source, the concept of space-based solar power (SBSP) is gaining increasing relevance. Once considered merely a science fiction concept, SBSP is now the subject of active research and development. This idea offers the prospect of an uninterrupted energy supply by capturing solar radiation in space, where it is continuous and unaffected by atmospheric conditions.

The SBSP concept involves placing PV panels in Earth's orbit, where they can continuously absorb solar energy and transmit it to Earth via microwave or laser technologies. Recent advancements in aerospace technologies and materials science are opening new possibilities for the realization of this concept.

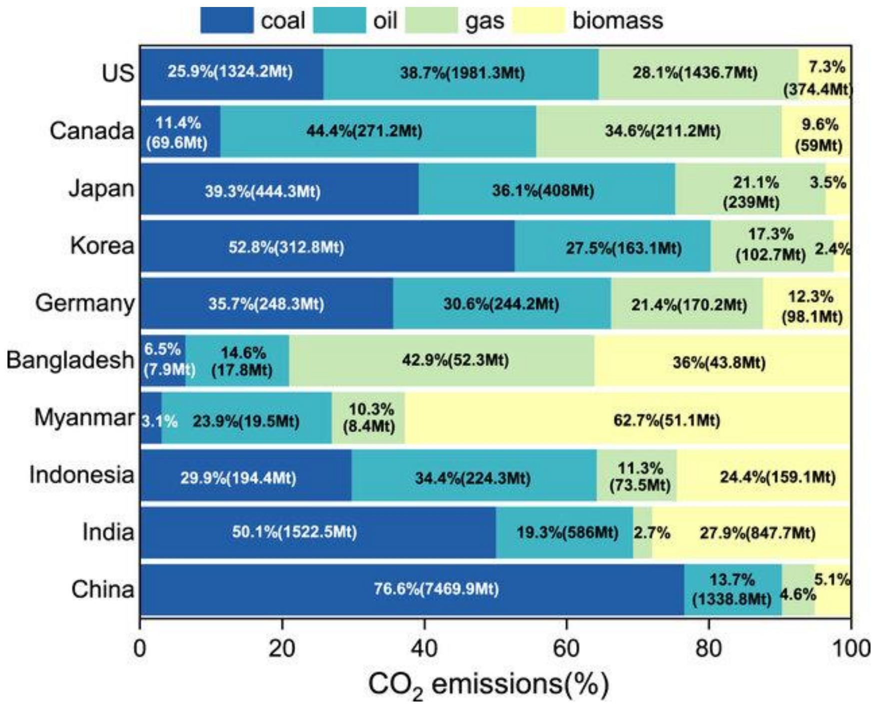

Fig. 1. The distribution of CO_2 emissions from fuel combustion – encompassing coal, oil, gas, and biomass – between five developing and five developed countries in 2017 [6]

The purpose of the study. This study will investigate the essential technical, economic, and environmental aspects of SBSP and evaluate its feasibility as a solution to global energy challenges. The focus will include an assessment of current technological advancements, as well as potential obstacles to SBSP implementation, to determine its viability in the near future.

The research will delve into SBSP technology, exploring its structure, components, significance, and necessity for achieving a sustainable future. It will trace the origins of SBSP, review existing developments, and analyze various conceptual approaches.

Methods. This study employed a combination of comparative analysis, expert evaluation, and statistical analysis of data. The data sources include scientific papers, reports from international analytical agencies, and publications from organizations focused on assessing the space-based solar power potential and challenges of space-based energy system development in various countries.

SBSP Principles

The Sun delivers approximately 1,37 kW/m² of solar irradiance [9]. With current terrestrial PV technologies, this amount has been estimated to be sufficient to meet today`s energy demands [10]. Consequently, for photovoltaic researchers, the primary objective is to enhance the efficiency of solar energy harvesting. This involves not only improving the intrinsic efficiency of PV devices but also addressing the inherent limitations of solar energy and exploring solutions to overcome them.

Terrestrial PV harvesting faces three primary limitations. First, a significant portion of sunlight is lost in the atmosphere due to scattering. Fig. 2 illustrates three distinct spectra: the AM0 spectrum observed just outside Earth`s atmosphere, the AM1,5 Direct spectrum at the equator under oblique incidence, and the AM1,5 Global spectrum averaged across the globe [11, 12]. Numerically, while AM0 illumination provides up to 1,37 kW/m², AM1,5 illumination peaks at 1,0 kW/m². The second challenge arises from the day-night cycle, which ensures that every location on Earth experiences periods when solar energy cannot be harvested. This limitation is further complicated by a third issue: electricity demand tends to increase in the evening [13-15], necessitating the storage of PV energy generated during the day, which introduces additional inefficiencies. These three constraints must be carefully considered and addressed when designing terrestrial PV panels.

Here, we introduce the concept of SBSP. Fig. 3 illustrates the operational schematic of this technology. SBSP involves placing an array of PV cells in orbit around the Earth to capture solar energy directly from space.

The harvested energy is then transmitted wirelessly to Earth, typically using a microwave-phased array transmitter. On Earth, the energy is received at rectenna stations and converted back into usable electricity [17, 18, 20, 26].

Collection and Conversion of Energy

The primary function of the system`s first stage would be to collect solar energy. This could be achieved using PV cells or mirrors on a large scale, potentially spanning kilometers. One of the most challenging aspects of this system is directing the collected photons toward the conversion mechanism, especially given that current PV cell technology does not yet meet the desired performance standards. Before the solar energy can be transmitted, it must be converted into either microwave or laser energy, which also requires appropriate power conditioning to enhance efficiency. While advancements in power electronics have streamlined the conversion process, further efficiency improvements are still needed [21]. High Concentration Photovoltaics (HCPV) could contribute to reducing the system`s mass, increasing conversion efficiency, and improving heat dissipation [23].

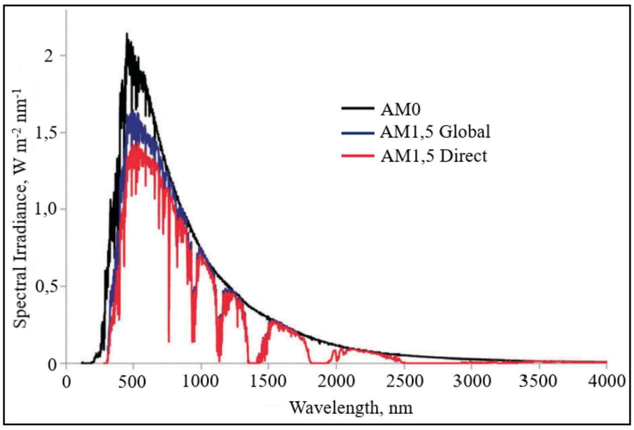

Fig. 2. Spectral plots of the AM0, AM1.5 Global, and AM1.5 Direct solar intensity spectra [11, 12]

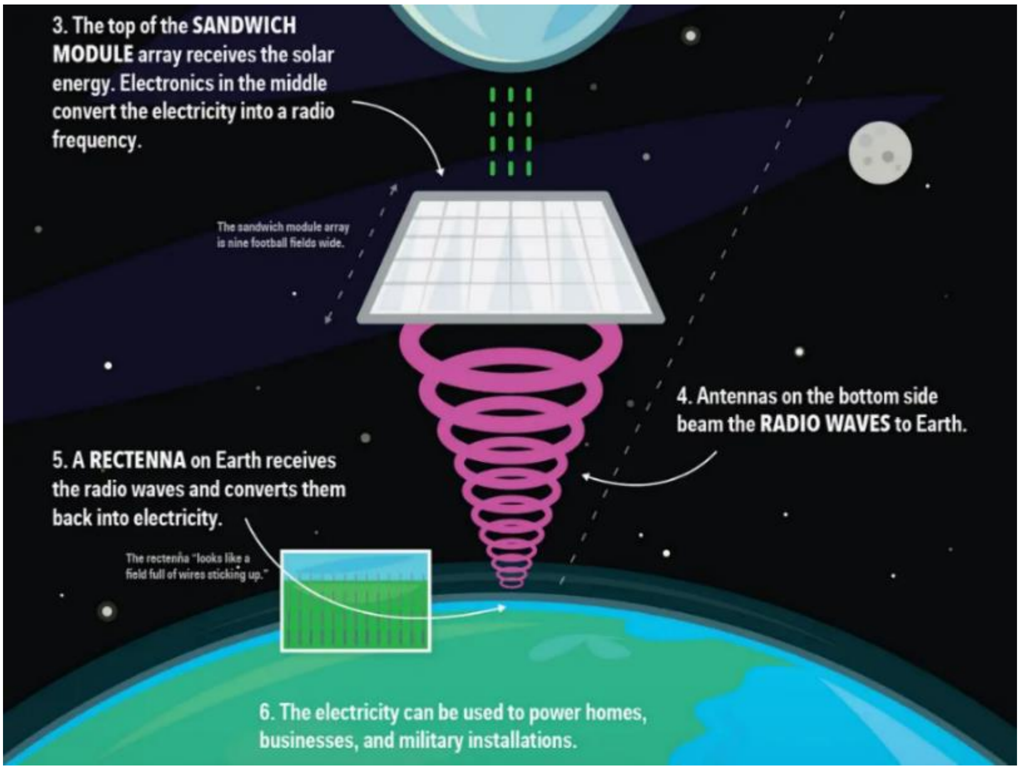

Fig. 3. Schematic illustrating the operating principles of SBSP [16]

Energy Transmission

This subsystem utilizes microwave power beams to transmit large amounts of power by converting electrical energy into non-ionizing radio frequencies (RF) and sending it from the satellite to the receiving station on Earth [23-26]. A critical focus must be on developing large, efficient power transmission antennas, as these technologies are inherently inefficient at small scales and cannot be fully validated without large-scale implementation. Although some testing has been conducted, further intensive research is needed to enhance the system`s efficiency and accuracy [27, 28, 50]. Producing a coherent beam on a flexible framework presents a significant technological challenge for the development of SBSP. Additionally, frequency bands must be allocated and agreed upon at the international level to prevent interference with existing systems.

The system is divided into several subsystems as shown in Fig. 4.

Satellite Control, Communication and Maintenance

Satellite maintenance and communication are critical components of the system, encompassing activities such as thermal management, station upkeep, and the operation of communication and control systems for the satellites.

Effective cooling of power electronics and other components is essential to enhance performance and reliability [29, 30]. However, the need for cooling systems in space is a subject of debate, and further testing is required to understand thermal load and heat dissipation in the space environment fully. Contemporary satellite technology may provide valuable insights into these challenges. Maintaining the satellite`s orbit would necessitate the use of thrusters [31, 32]. For massive structures, scaling and refining technology is a significant issue, requiring advancements to reduce structural bulk while maintaining station integrity. This could be achieved through the use of electric thrusters and mechanical damping systems.

Satellite control demands the integration of sensors, control logic, and processing units. The control system for this application is expected to be far more sophisticated than those used in existing satellites [33]. Additional sensors will likely be required to support control systems and respond to unforeseen threats. Developing resource management strategies for regulating the antenna beam while ensuring system security will also be necessary [34]. Constant communication between the satellites and Earth is crucial for system control and monitoring. Fortunately, with the advancements in modern communication technologies, communication systems are expected to be among the least challenging aspects of the overall system [35-37].

Maintaining Angle

In a Geostationary Earth Orbit (GEO), an SBSP maintains a constant angle concerning Earth. However, the angle between the sun-facing solar collector and the Earth-facing microwave transmitter continuously changes. To ensure that the solar collector remains aligned with the sun, the microwave beam must always be accurately aimed at the intended location on Earth. Conversely, if the microwave beam is aimed at a fixed point on Earth, the solar collector must continuously face the sun [18, 38]. Solutions to this challenge include mechanical steering and solid-state electrical beam steering.

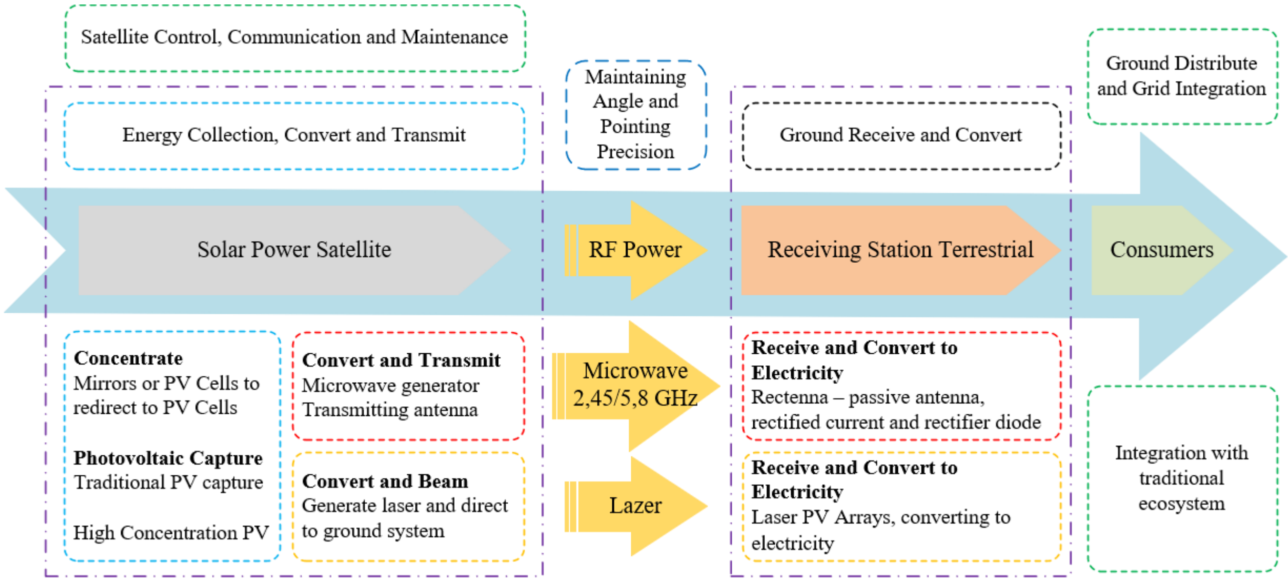

Fig. 4. System Structure Diagram [18]

Pointing Precision

For designs using mirrors as solar collectors, maintaining precise alignment is crucial to ensure high solar intensity on the PV components. The mirrors must be aligned with extreme precision to prevent localized hotspots on the PV components, which could affect performance [18, 39].

Ground Receives and Converters

Ground systems are generally easier to construct and maintain compared to space systems. The rectenna, which converts the transmitted microwave beam into electrical energy, is a key component of the ground-based receiving system. Developing this technology is challenging due to the lack of experience and knowledge in significant rectenna technology and the inability to test it in Earth's orbit. To reduce the size of the space structure, a large antenna area on Earth is required. Although a smaller rectenna could be used, it would only capture a portion of the transmitted energy. The size of both the satellite antenna and the Earth's rectenna are interconnected due to diffraction physics. Tests have shown that the concept is theoretically viable [18, 40-44].

Terrestrial Distributed and Grid Integration

To integrate the energy into the grid, power conditioning and reactive power control techniques similar to those used in PV stations are employed. The simplest step involves using transformers and transmission lines to collect and deliver electricity from the site to the power grid, utilizing existing infrastructure. A control station will oversee the satellite, power transmission, conversion, distribution, and data monitoring [18].

Based on Laser

Laser-based systems operate on a similar principle. In lower orbits, the satellite will pass over multiple countries. The project would need to be a multinational effort, or energy harvesting would be limited to specific times. In this system, solar energy is converted into laser beams by solid-state laser systems, which are then directed to a ground station where they are converted into electrical energy [45, 46].

Mission Flexibility

The design of a SBSP satellite can be tailored to its target orbit to optimize power generation and utilization across its operational period. For instance, satellites in Geostationary Earth Orbit (GEO) are designed to maximize power output and provide continuous energy, leveraging the stable orbital position. In contrast, satellites placed in Low Earth Orbit (LEO) or Medium Earth Orbit (MEO) offer greater adaptability, allowing for a more flexible approach to energy provision while potentially reducing costs. This adaptability can enable mission flexibility, allowing for smaller-scale development satellites to cater to a variety of applications. Such applications include supplying power to research facilities in remote or polar regions where fuel costs are prohibitively high, supporting disaster relief efforts, and meeting the energy needs of military operations. By employing different orbits and leveraging the specific advantages of each, the SBSP system can address diverse energy requirements and enhance overall mission versatility [47].

Materials and Technology Innovations

Materials and technology used in SBSP systems represent significant challenges. Although the foundational technologies are in place, their performance still requires substantial enhancement. Currently, space stations and satellites use PV panels, and while lightweight gallium arsenide (GaAs) PV cells are commercially available with efficiencies of around 30-35%, these levels are still inadequate for the demanding requirements of SBSP applications [18, 48].

Regarding rectenna technology, size, and cost have historically posed challenges. However, recent advancements suggest progress in this area. On March 3, researchers at Caltech successfully demonstrated wireless power transfer using an array of lightweight, flexible microwave power transmitters. These transmitters were powered by specially designed electronic chips fabricated with cost-effective silicon technologies. The system utilized a network of transmitters to direct energy to specific target areas [49]. Such experiments are becoming increasingly common as advancements in electronics technology enhance their efficiency and feasibility.

Challenges, risks and issues of SBSP Concept

The SBSP concept faces several significant challenges that must be addressed to realize its potential as a viable energy solution. The development of SBSP is inherently complex due to the immense scale and the intricate integration requirements of the system. Once completed, the solar power satellite is expected to be the largest and heaviest structure in orbit, making the power-to-mass ratio (kW/kg) a critical performance metric. Achieving a low system mass while ensuring efficient power transmission from solar photovoltaic panels in space to the electrical grid is essential for the viability of SBSP. This requires innovative materials, advanced engineering, and rigorous proof-of-concept demonstrations to validate the technology's effectiveness in real-world applications.

Although still in its nascent and costly stage [17, 18], SBSP has the potential to overcome the limitations of terrestrial PV power. Firstly, energy is harvested from space, where the intensity of sunlight is greater, resulting in higher PV power yield. Secondly, unlike ground-based PV panels, space-based systems are not subject to the Earth`s day-night cycle. By positioning the cells in a suitable orbit – such as a geostationary or low Earth orbit [17, 18, 26] – the panels can avoid shadowing and ensure continuous sunlight exposure. Finally, the ability to transmit power continuously from space allows for consistent energy delivery to areas on Earth that are experiencing nighttime, thus addressing energy storage challenges.

Economic

The primary challenge to the broader adoption of SBSP is the high cost of launching PV cells, or any payload, into space. Despite increasing demand for private space missions and significant efforts to commercialize space travel, launch costs remain substantial, ranging from USD 1,400/kg to over USD 50,000/kg [19, 20]. This significantly impacts the cost per Watts of PV panels for SBSP, adding to the manufacturing costs. Consequently, much of the research and development in this area focuses on reducing the mass and areal density (mass per unit area) of PV panels [19, 26]. The mass per unit area is directly related to the power generated per unit area of the cell, which leads to the important metric of specific power, or power generated per unit mass.

The total cost of implementing SBSP is influenced by a multitude of factors, including construction, operation, and maintenance expenses, as well as the system's projected lifespan. A critical metric in evaluating these costs is the Levelized Cost of Energy (LCOE), which provides a comprehensive measure of the lifetime costs of electricity generation. LCOE is calculated by dividing the total lifetime cost of a power plant by the total energy output over its operational lifespan, making it an essential tool for comparing the economic viability of different energy technologies.

For example, the estimated cost of the CASSIOPeiA project is reported to be £16.3 billion, with an LCOE of £50/MWh, while the SPS-ALPHA project is estimated to cost $11.4 billion, with an LCOE of $5.50 per Watt [18]. However, these estimates are from studies conducted in 2021 and 2017, respectively, and one of the significant cost components for SBSP is transportation, which is rapidly decreasing as more private companies enter the space industry. Consequently, the actual costs and LCOE can only be accurately determined once a project is initiated.

Furthermore, LCOE can vary significantly depending on geographic and environmental factors. For example, the LCOE for large-scale solar power in the UK is approximately £33/MWh, whereas in the US, it ranges from $24 to $96/MWh depending on the state. Similarly, the LCOE for offshore wind in the UK is around £33/MWh, compared to

$72 to $140/MWh in the US [18]. This variability underscores the importance of context-specific evaluations when considering the economic feasibility of SBSP projects.

Technological

The development of SBSP does not require groundbreaking scientific or technological innovations, but it does demand significant advancements in several critical areas. These challenges pose substantial obstacles to realizing the SBSP vision.

The gravitational force from Earth decreases with distance, but celestial bodies such as the Moon and Sun still exert gravitational influences. Space debris and solar radiation pose significant concerns [26, 51].

The size and mass of SBSP systems necessitate the construction of key components in orbit, yet humanity has not ventured into upper Earth orbit [20].

The assembly and maintenance of such large structures in space will require advanced robotics capable of operating autonomously in the harsh space environment. Given the scale of SBSP systems, a lightweight, large-scale framework that can be constructed by robots while maintaining structural rigidity is crucial [20, 52, 53].

Orbital location is a key consideration when launching such structures. LEO, at altitudes of approximately 2,000 km or less [54, 55], would require a cluster of 3-13 modules or international collaboration to ensure continuous energy conversion, though this could disrupt 24/7 supply [26]. The stronger gravitational force in LEO necessitates additional fuel for station maintenance. MEO, with satellite periods ranging from 6 to 12 hours, provides a more extended presence over specific Earth regions [56].

GEO, about 36,000 km from Earth, allows a satellite or SBSP module to orbit at the same speed as Earth`s rotation [54]. Once positioned in GEO, the module remains stationary relative to Earth, though initial testing will occur at lower orbits. GEO, despite higher launch costs, offers a continuous power supply with just one module for a specific location, making it a preferable choice for SBSP despite its higher expense [26].

Current rocket and thruster technologies are not yet efficient or powerful enough to transfer large structures from lower to higher orbits easily. To address these challenges, smaller and lighter panels must be developed to simplify construction and reduce costs. Additionally, the satellite's operational lifetime must be maximized to ensure that the investment is economically viable.

For wireless power transmission, microwave-based systems are applicable in all orbits, while laser-based systems are limited to lower orbits. Challenges associated with laser-based technologies include safety, environmental, and legal concerns. Thus, microwave-based transmission is the primary focus [57, 58]. The efficiency of wireless power transfer is crucial, as the project was conceived due to the lower efficiency of conventional solar plants. Improving wireless power transfer technologies is essential for minimizing energy losses during transmission from space to Earth.

PV and solar dynamic (SD) energy conversion methods are explored, with PV technology being prioritized [59]. PV technology, using semiconductor materials like silicon to convert sunlight into electricity, is favored for its simplicity, low maintenance, and adaptability. However, PV systems face issues like limited efficiency, substantial weight, and sensitivity to temperature fluctuations. SD systems, which use mirrors to concentrate light onto a working fluid and generate electricity through a heat engine, could reduce overall system mass but introduce their challenges [60]. The complexity and maintenance requirements of SD systems, along with the need for precise alignment, make them less favorable. Microwave transmission, being safe for human exposure at the proposed frequency [61, 62], is preferred. The beam targets the ground where it is captured by a rectenna, converting microwaves into electricity that is then adapted for grid delivery.

Lastly, cybersecurity poses a significant challenge. Software bugs and vulnerabilities could compromise the precision and performance of SBSP systems. Therefore, robust and secure software, with built-in redundancy, is essential to prevent satellites from transmitting at unsafe power levels or being compromised by cyberattacks.

In summary, while SBSP is scientifically feasible, overcoming these technological and logistical challenges is critical for its successful development and deployment.

Political

The project will be influenced by both local and global political factors. On a local level, integrating a SBSP system with existing infrastructure and aligning it with current energy policies presents significant challenges. Given that the project will span decades before producing tangible results, the development timeline must be meticulously planned to ensure long-term viability.

One of the key local concerns is the need for large tracts of land for Earth-receiving stations, particularly the rectennas. The allocation and security of this land must be carefully managed to avoid conflicts and ensure continuous operation. Space security is another critical factor, as the infrastructure in orbit will require protection from both physical and cyber threats.

On a global scale, international collaboration will be essential for the project's success. By sharing the costs, risks, and benefits among participating nations, the project can not only foster economic growth but also enhance global energy security. Collaborative efforts can also help overcome political and regulatory hurdles, ensuring that the project progresses smoothly despite its lengthy timeline.

Most nations currently have vague or underdeveloped regulations regarding SBSP. This lack of regulatory clarity can deter inventors and businesses from investing in SBSP technology, as the risks associated with regulatory uncertainty are significant. One of the primary regulatory challenges is wireless power transmission, which would fall under the jurisdiction of national government agencies and require international coordination through bodies like the International Telecommunications Union (ITU).

Wireless communication is primarily regulated to manage device and broadcast interference, and countries will need to adapt their regulatory frameworks to accommodate wireless power transmission. This adaptation will involve recognizing that wireless power transmission should fit within the existing regulatory structures. To prevent interference with existing technologies and communications, it will be necessary to negotiate appropriate frequency allocations and conduct thorough testing to identify and mitigate potential impacts on affected equipment and communications systems.

Publical

Large-scale projects require robust public support, particularly when addressing the safety and security concerns linked to wireless power transfer. Key issues often include the potential effects of wireless transmissions on human health and the safety of aircraft, wildlife, and infrastructure. However, SBSP systems are meticulously designed to mitigate these risks, ensuring they do not endanger living beings or physical structures. In essence, the technology employed in SBSP systems, which utilizes low-power microwave transmission, is comparable in wavelength to that used in common household devices but operates at a significantly lower signal strength. As such, the safety concerns associated with SBSP are minimal and analogous to those related to everyday technologies.

SBSP System Concept Architectures

Various organizations are actively developing conceptual satellite designs. Below, we discuss some of the most recent advancements in this area.

Sandwich module

The «sandwich module», originally investigated during NASA/DOE research in the late 1970s, serves as the primary component of various modular SBSP designs [27, 63, 64, 67]. This module carries out essential functions that can be categorized into three distinct layers: first, accumulating solar energy and converting it into direct current electricity; second, generating an RF signal with the appropriate magnitude and frequency for transmission; and third, forming a spaceborne transmission array aperture capable of achieving sufficient beam coupling to deliver useful energy to the ground. A simple, basic illustration of a sandwich module is depicted in Fig. 5.

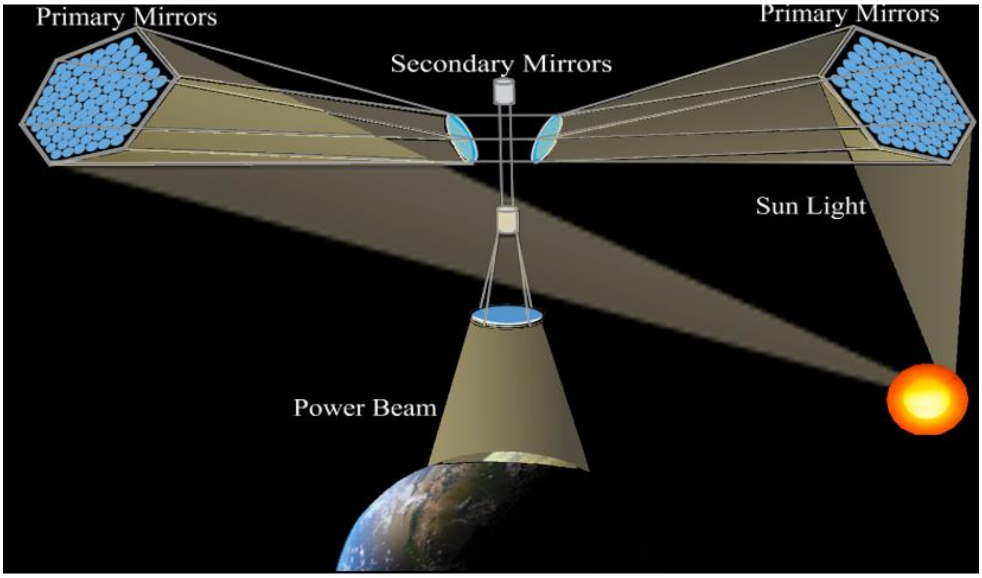

Fig. 5. NASA`s Sandwich Model Concept [18]

Solar Power Satellite via Arbitrarily Large-Phased Array

Solar Power Satellite via Arbitrarily Large Phased Array (SPS-ALPHA) is a concentrator design that leverages a gravity gradient-stabilized approach to separate the mirror mass from the sandwich panel by several kilometers. The sandwich panel in SPS-ALPHA is designed like a thin-film reflector and is permanently oriented toward Earth for electricity transmission. To direct sunlight onto the photovoltaics within the sandwich panel, the design employs heliostats—motorized, individually adjustable mirrors that respond to the Sun's shifting position relative to the Earth. By adjusting the satellite operator's position, the amount of light reaching the panels can be controlled, which is crucial for managing thermal load. The design also incorporates 10 types of standard modules, facilitating deployment, assembly, and maintenance. By eliminating single points of failure, the design allows for gradual degradation. The system is capable of delivering 2 GW of microwave power through an antenna with a diameter of 1.7 km, paired with a 6 km wide rectenna on Earth. The total mass of the system is estimated at 8,000 tons. The satellite is intended to orbit in GEO to ensure consistent power delivery. The design is expected to have a lifespan of 100 years, with the flexibility for component replacements as needed. Fig. 6 illustrates the SPS-ALPHA design concept [17, 18, 20, 64-66].

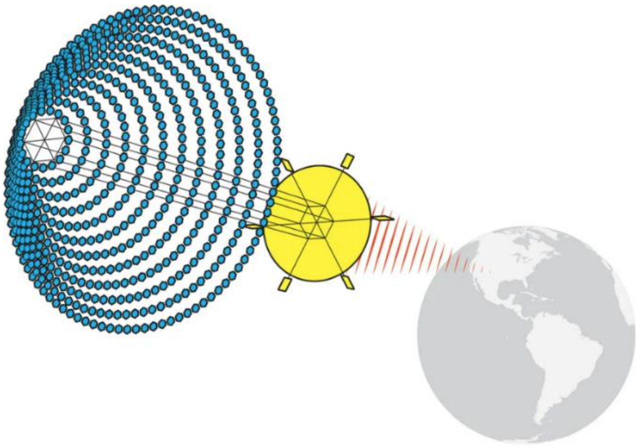

Fig. 6. NASA physicist John C. Mankins` SPS-ALPHA Mark-III Concept [67]

Multi-rotary solar power satellite

The Multi-Rotary Solar Power Satellite (MR-SPS) is designed to optimize solar energy collection and transmission without relying on a traditional solar concentrator system. Instead, the MR-SPS employs a series of large solar panels supported by rotary joints, allowing these panels to rotate around a single axis independently of the satellite's main framework. This innovative design enables continuous exposure to the Sun, maximizing energy collection throughout the satellite's orbit and facilitating precise alignment of the transmission array for efficient beam steering and power transfer to Earth.

With a capacity of 1 GW, the MR-SPS features a structure spanning 11.8 kilometers in width and weighing approximately 10,000 tonnes. It operates in GEO and includes a 1 km diameter antenna and a 5 km wide rectenna on Earth. The design incorporates advanced thermal control mechanisms to manage the heat generated by the concentrated solar energy and distributes the solar load across multiple rotating panels, addressing issues related to energy density and thermal management.

The modular construction of the MR-SPS supports scalability and adaptability, allowing adjustments to meet varying energy demands and operational conditions. Although the design eliminates the need for a complex solar concentrator setup, it introduces significant technological challenges, particularly concerning the robustness of the rotating joints and the extensive power distribution system. Considerable effort has been directed toward overcoming these challenges.

The MR-SPS is projected to have an operational lifespan of thirty years, making it a promising candidate for future space-based solar power applications [17, 18, 20, 65]. Fig. 7 illustrates the MR-SPS design concept.

Constant aperture solid-state integrated orbital phased array

The Constant Aperture Solid-State Integrated Orbital Phased Array (CASSIOPeiA) is a cutting-edge satellite design tailored for space-based solar power systems. This advanced concept features a continuous, solid-state phased array with a constant aperture, optimizing the efficiency of energy transmission from space to Earth. The CASSIOPeiA satellite integrates HCPV panels mounted on a helical structure oriented north-south. This orientation, coupled with circular thin-film reflectors, enables the panels to capture solar rays reflected by mirrors positioned on either side of the structure, ensuring a steady supply of electricity.

The satellite's design includes a collection of microwave-emitting antennas configured as an orientable phased array, which allows for 360° steering of the microwave beam. These antennas work in synchrony to direct the beam as the satellite rotates relative to Earth. This solid-state system is devoid of moving components, with orbit stability achieved through the adjustment of solar pressure on the mirrors using electrochromic materials.

The modular construction of CASSIOPeiA, consisting of five common module types, supports robotic assembly and deployment. This design addresses heat management and power distribution challenges by utilizing a modular dispersed approach, thereby eliminating single points of failure and allowing for gradual degradation over time. Each module integrates both PV cells and RF dipoles, contributing to a high specific power rating and optimizing the use of modules while reducing the total amount of PV required. The satellite is designed to be maintenance-free, with provisions for graceful aging throughout its lifespan.

For a 2 GW system, the estimated mass is approximately 2,000 tonnes, featuring a 1,6 km wide antenna and a 5 km rectenna. The innovative use of HCPV panels, along with the modular and dispersed design, enhances the satellite's efficiency and reliability. Fig. 8 illustrates the CASSIOPeA design concept [18, 64, 67, 68].

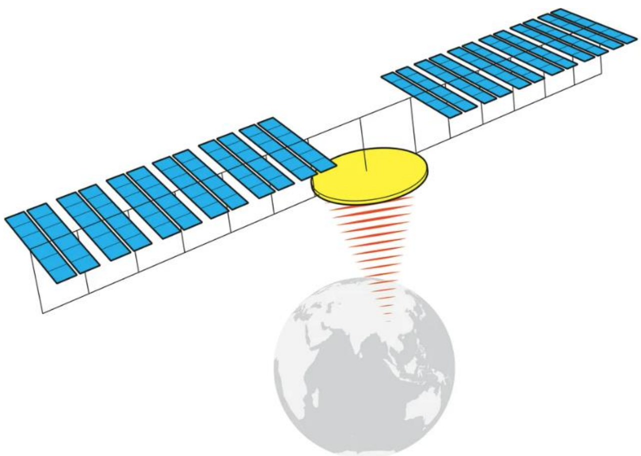

Fig. 7. China Academy of Space Technology`s MR-SPS Concept [67]

The CASSIOPeiA and MR-SPS space-based solar power concepts are both immense in size, especially when compared to well-known structures like the International Space Station (ISS), the Eiffel Tower, and the Burj Khalifa.

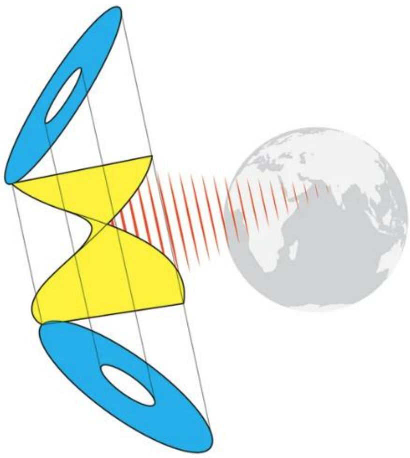

Fig. 8. Space Solar Group Holdings Chief Architect Ian Cash`s CASSIOPeiA Concept [67]

The CASSIOPeiA design features an antenna with a diameter of 1.6 kilometers, which is about 14.7 times the length of the ISS, nearly five times the height of the Eiffel Tower, and almost twice the height of the Burj Khalifa. Its rectenna, spanning 5 kilometers, is 45.8 times the length of the ISS, 15.15 times the height of the Eiffel Tower, and six times the height of the Burj Khalifa.

In contrast, the MR-SPS concept has a structure width of 11.8 kilometers, which is 108 times the length of the ISS, 35.8 times the height of the Eiffel Tower, and 14.25 times the height of the Burj Khalifa. The MR-SPS antenna, with a diameter of 1 kilometer, is 9.2 times the length of the ISS, three times the height of the Eiffel Tower, and slightly taller than the Burj Khalifa. Its rectenna, like that of CASSIOPeiA, is 5 kilometers wide, further emphasizing the vast scale of these systems.

Both the CASSIOPeiA and MR-SPS concepts dwarf these iconic structures, illustrating the extraordinary size and complexity required for space-based solar power systems. The MR-SPS, with its massive 11.8-kilometer width, stands out as particularly immense, while CASSIOPeiA also demonstrates significant scale, especially when compared to familiar landmarks like the ISS, the Eiffel Tower, and the Burj Khalifa (Fig. 9).

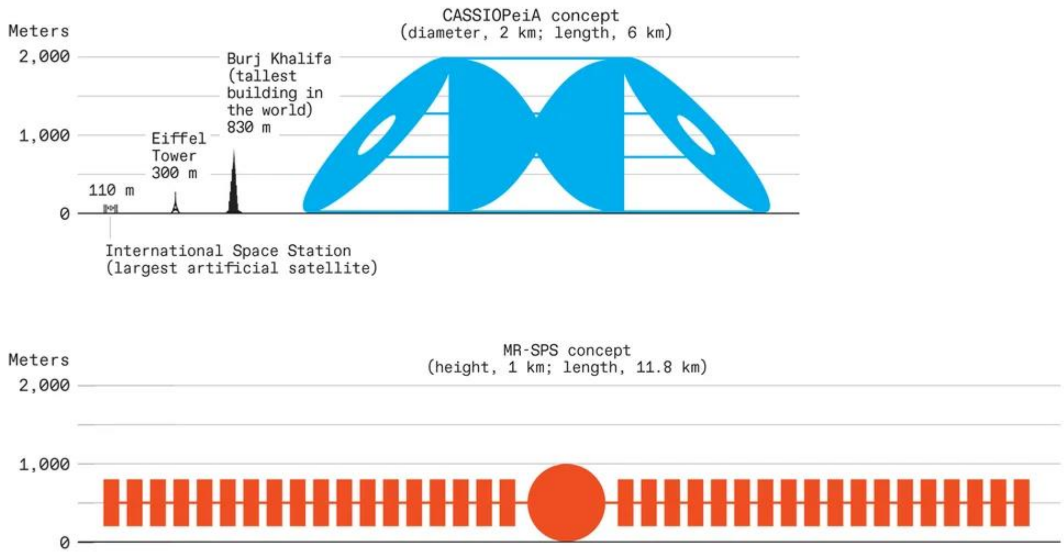

Fig. 9. A comparison of the CASSIOPeiA and the MR-SPS Concepts` sizes, relative to the highest points on Earth [67]

Conclusions

SBSP presents a transformative opportunity to achieve net-zero emissions by 2050, with its potential to provide a continuous, weather-independent power supply. This paper underscores the significant advancements in SBSP technology, such as reusable rockets, more efficient PV cells, and the reduction in manufacturing costs. These developments have moved SBSP from a concept once deemed too costly and complex to a promising solution for global energy demands. Despite these advances, considerable challenges remain, particularly in wireless power transmission and the deployment of large-scale systems. Further research and global collaboration are essential to overcoming these obstacles and realizing SBSP's full potential as a clean, sustainable energy source. The paper concludes that with strategic planning and sustained efforts, SBSP could play a pivotal role in addressing the future energy crisis.

REFERENCES

1. D. Gielen et al., «Global energy transformation: A roadmap to 2050», International Renewable Energy Agency (IRENA), 2019.
2. P. R. Shukla et al., «Climate change and land: An IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems», Intergovernmental Panel on Climate Change (IPCC), 2019.
3. D. Tong et al., «Targeted emission reductions from global super-polluting power plant units», Nature Sustainability, vol. 1, no. 1, pp. 59-68, 2018, doi: 10.1038/s41893-017-0003-y.
4. X. Li, J. Zhou, B. Duan, Y. Yang, Y. Zhang, and J. Fan, «Performance of planar arrays for microwave power transmission with position errors», IEEE Antennas and Wireless Propagation Letters, vol. 14, pp. 1794-1797, 2015, doi: 10.1109/LAWP.2015.2424227.

5. Z. Salameh, «Emerging renewable energy sources», in Renewable energy system design, pp. 299-371, 2014, doi: 10.1016/B978-0-12-374991-8.00005-2.
6. S. Li et al., «The driving forces behind the change in energy consumption in developing countries», Environmental Research Letters, vol. 16, 2021, doi: 10.1088/1748-9326/abde05.
7. D. Gielen, F. Boshell, D. Saygin, M. D. Bazilian, N. Wagner, and R. Gorini, «The role of renewable energy in the global energy transformation», Energy Strategy Reviews, vol. 24, pp. 38-50, 2019, doi: 10.1016/j.esr.2019.01.006.
8. «Weather», Available: https://science.jrank.org/pages/7326/Weather-Solar-energy.html.
9. E. Robens, E. H. Nokraschy, and A. Dabrowski, «Energy & climate», Annales Universitatis Mariae Curie-Sklodowska: Chemia, Sectio AA, vol. 63, p. 94, 2008, doi: 10.2478/v10063-009-0002-6.
10. A. Maka and J. Alabid, «Solar energy technology and its roles in sustainable development», Clean Energy, vol. 6, pp. 476-483, 2022, doi: 10.1093/ce/zkac023.
11. K. Mazzio and C. Luscombe, «Correction: The future of organic photovoltaics», Chemical Society Reviews, 2014, doi: 10.1039/c4cs00227j.
12. D. Leitão, J. P. N. Torres, and J. F. P. Fernandes, «Spectral irradiance influence on solar cells efficiency», Energies, vol. 13, no. 19, p. 5017, 2020, doi: 10.3390/en13195017.
13. S. Lee, D. Whaley, and W. Saman, «Electricity demand profile of Australian low energy houses», Energy Procedia, vol. 62, pp. 10-16, 2014, doi: 10.1016/j.egypro.2014.12.370.
14. J. Kang and D. M. Reiner, «What is the effect of weather on household electricity consumption? Empirical evidence from Ireland», Energy Economics, vol. 111, p. 106023, 2022, doi: 10.1016/j.eneco.2022.106023.
15. G. Yan and L. Han, «The impact of rooftop solar on wholesale electricity demand in the Australian National Electricity Market», Frontiers in Energy Research, vol. 11, p. 1197504, 2023, doi: 10.3389/fenrg.2023.1197504.
16. K. Jennings, «What if giant space-based solar panels could beam unlimited power to the Earth?», Business Insider, 2014. Available: https://www.businessinsider.com/space-based-solar-panels-could-power-earth-2014-7.
17. B. Kruft, «A techno-economic analysis of space-based solar power systems», Junior Management Science (JUMS), vol. 8, no. 3, pp. 732-771, 2023, doi: 10.5282/jums/v8i3 pp732-771.
18. K. S. Alam et al., «Towards net zero: A technological review on the potential of space-based solar power and wireless power transmission», Heliyon, vol. 10, no. 9, p. e29996, 2024, doi: 10.1016/j.heliyon.2024.e29996.
19. W. Whitman Cobb, «How SpaceX lowered costs and reduced barriers to space», The Conversation, 2019. Available: https://theconversation.com/how-spacex-lowered-costs-and-reduced-barriers-to-space-112586.
20. E. Kulu, «Space Solar Power - 2023 Survey of Public and Private Initiatives», presented at the 74th International Astronautical Congress (IAC 2023), 2023.
21. M. V. Reddy, «Microwave power transmission – A next generation power transmission system», IOSR Journal of Electrical and Electronics Engineering, vol. 4, no. 5, pp. 24-28, 2013, doi: 10.9790/1676-0452428.
22. S. Zimmermann et al., «A high-efficiency hybrid high-concentration photovoltaic system», International Journal of Heat and Mass Transfer, vol. 89, pp. 514-521, 2015, doi: 10.1016/j.ijheatmasstransfer.2015.04.068.
23. C. R. Valenta and G. D. Durgin, «Harvesting wireless power: Survey of energy-harvester conversion efficiency in far-field, wireless power transfer systems», IEEE Microwave Magazine, vol. 15, no. 4, pp. 108-120, 2014, doi: 10.1109/MMM.2014.2309499.
24. R. K. Mishra and A. K. Mishra, «Space based Solar Power: Feasibility Microwave based wireless power system», Journal of Marine Science and Research, vol. 2, no. 1, 2023, doi: 10.58489/2836-5933/005.
25. E. Rodgers et al., «Space-based solar power», NASA, Washington, DC, Report No. 20230018600, pp. 91, 2024.
26. E. Gregersen, «Space-Based Solar Power», Encyclopedia Britannica, 2024. Available: https://www.britannica.com/technology/space-based-solar-power.
27. J.-M. Choi, S.-J. Choi, and S.-H. Yi, «Case studies on space solar power in Korea», Space Solar Power and Wireless Transmission, vol. 1, no. 1, pp. 27-36, 2024, doi: 10.1016/j.sspwt.2024.03.001.
28. C. Yang and Q. Yu, «Placement and size-oriented heat dissipation optimization for antenna module in space solar power satellite based on interval dimension-wise method», Aerospace Science and Technology, vol. 134, p. 108155, 2023, doi: 10.1016/j.ast.2023.108155.
29. C. Yang, X. Hou, and S. Chang, «A synchronous placement and size-based multi-objective optimization method for heat dissipation design on antenna module of space solar power satellite», Sustainable Energy Technologies and Assessments, vol. 45, p. 101183, 2021, doi: 10.1016/j.seta.2021.101183.
30. S. Borissov, Y. Wu, and D. Mortari, «East–West GEO satellite station-keeping with degraded thruster response», Aerospace, vol. 2, no. 4, pp. 581-601, 2015, doi: 10.3390/aerospace2040581.
31. K. Sato et al., «The collision avoidance strategy for geostationary satellites considering orbit maintenance», Journal of Space Safety Engineering, vol. 8, no. 4, pp. 331-338, 2021, doi: 10.1016/j.jsse.2021.08.004.
32. X. Ji et al., «Attitude control of space solar power satellite with large range of relative motion among subsystems», Aerospace Science and Technology, vol. 100, p. 105781, 2020, doi: 10.1016/j.ast.2020.105781.
33. P. Si and Y. Zeng, «Electric propulsion for low Earth orbit operations», Progress in Aerospace Sciences, vol. 143, p. 101838, 2023, doi: 10.1016/j.paerosci.2023.101838.
34. A. Badescu, «Mathematical modeling of energy consumption using Gompertz function: The case of Brazil», International Journal of Energy Economics and Policy, vol. 11, no. 1, pp. 1-6, 2021, doi: 10.32479/ijeep.10683.
35. M. Khammassi, A. Kammoun, and M.-S. Alouini, «Precoding for high-throughput satellite communication systems: A survey», IEEE Communications Surveys & Tutorials, vol. 26, no. 1, pp. 80-118, 2024, doi: 10.1109/COMST.2023.3316283.
36. A. Algaba-Brazalez, P. Castillo-Tapia, M. C. Vigano, and O. Quevedo-Teruel, «Lenses combined with array antennas for the next generation of terrestrial and satellite communication systems», IEEE Communications Magazine, pp. 1-7, 2023, doi: 10.1109/MCOM.024.2300370.
37. R. Samy, H.-C. Yang, T. Rakia, and M.-S. Alouini, «Hybrid SAG-FSO/SH-FSO/RF transmission for next-generation satellite communication systems», IEEE Transactions on

Vehicular Technology, vol. 72, no. 11, pp. 14255-14267, 2023, doi: 10.1109/TVT.2023.3281256.

38. X. Meng et al., «Optical study of a cocktail structural space-based solar power station», Solar Energy, vol. 194, pp. 156-166, 2019, doi: 10.1016/j.solener.2019.10.053.
39. Q. Li, Z. Deng, K. Zhang, and B. Wang, «Precise attitude control of multi rotary-joint solar-power satellite», Journal of Guidance, Control, and Dynamics, vol. 41, no. 6, pp. 1435-1442, 2018, doi: 10.2514/1.G003309.
40. A. Takacs, H. Aubert, L. Despoisse, and S. Fredon, «Design and implementation of a rectenna for satellite application», in 2013 IEEE Wireless Power Transfer (WPT), 2013, pp. 183-186, doi: 10.1109/WPT.2013.6556913.
41. G. Franceschetti, P. Rocca, F. Robol, and A. Massa, «Innovative rectenna design for space solar power systems», in 2012 IEEE MTT-S International Microwave Workshop Series on Innovative Wireless Power Transmission: Technologies, Systems, and Applications, 2012, pp. 151-153, doi: 10.1109/IMWS.2012.6215773.
42. E. Shi, E. Centeno, R. Figueroa, C. Qi, and G. Durgin, «A rectenna using copper foil on glass to reduce cost of space solar power», in 2019 IEEE Wireless Power Transfer Conference (WPTC), 2019, pp. 421-425, doi: 10.1109/WPTC45513.2019.9055554.
43. Y. Homma et al., «New phased array and rectenna array systems for microwave power transmission research», in 2011 IEEE MTT-S International Microwave Workshop Series on Innovative Wireless Power Transmission: Technologies, Systems, and Applications, 2011, pp. 59-62, doi: 10.1109/IMWS.2011.5877091.
44. J. D.-y. Dakora, I. E. Davidson, and G. Sharma, «Review of modern solar power satellite and space rectenna systems», in 2020 International Conference on Artificial Intelligence, Big Data, Computing and Data Communication Systems (icABCD), 2020, pp. 1-5, doi: 10.1109/icABCD49160.2020.9183884.
45. L. M. Jenkins, «Concepts for demonstration of wireless power transfer for space-based solar power», in 2011 Aerospace Conference, 2011, pp. 1-5, doi: 10.1109/AERO.2011.5747305.
46. Y. A. Abdel-Hadi, «Space-based solar laser system simulation to transfer power onto the earth», NRIAG Journal of Astronomy and Geophysics, vol. 9, no. 1, pp. 558-562, 2020, doi: 10.1080/20909977.2020.1815497.
47. B. Abiri et al., «A lightweight space-based solar power generation and transmission satellite», arXiv, 2022, doi: 10.48550/arXiv.2206.08373.
48. J. Li et al., «A brief review of high efficiency III-V solar cells for space application», Frontiers in Physics, vol. 8, p. 631925, 2021, doi: 10.3389/fphy.2020.631925.
49. Caltech, «In a first, Caltech's space solar power demonstrator wirelessly transmits power in space», 2023. [Online]. Available: https://www.caltech.edu/about/news/in-a-first-caltechs-space-solar-power-demonstrator-wirelessly-transmits-power-in-space.
50. Enel Green Power, «Space, the new frontier of photovoltaics», 2024. [Online]. Available: https://www.enelgreenpower.com/media/news/2024/05/photovoltaic-energy-space.
51. Y. Akahoshi et al., «Influence of space debris impact on solar array under power generation», International Journal of Impact Engineering, vol. 35, no. 12, pp. 1678-1682, 2008, doi: 10.1016/j.ijimpeng.2008.07.048.
52. B. Abiri et al., «A lightweight space-based solar power generation and transmission satellite», arXiv, 2022, doi: 10.48550/arXiv:2206.08373.
53. Y. Shi, X. Hou, X. Rao, and L. Li, «Research on the key technology of crawler robot orbiting on space solar power station», in 2018 IEEE International Conference on Mechatronics and Automation (ICMA), 2018, pp. 936-941.
54. Anywaves, «LEO vs. MEO vs. GEO satellites: What's the difference?», Feb. 1, 2024. [Online]. Available: https://anywaves.com/resources/blog/leo-meo-geo-satellites-definition-difference.
55. NASA, «Commercial space frequently asked questions: Commercial low earth orbit development program», 2024. [Online]. Available: https://www.nasa.gov/humans-in-space/leo-economy-frequently-asked-questions.
56. S. Gosavi, H. G. Mane, A. S. Pendhari, and A. Husainy, «A review on space-based solar power», Journal of Technology and Engineering Sciences, vol. 6, no. 1, 2021, doi: 10.46610/JoTES.2021.v06i01.003.
57. A. Baraskar, «Wireless Power Transmission Options For Space Solar Power», 2013.
58. S. Sasaki and K. Tanaka, «Wireless power transmission technologies for solar power satellite», in 2011 IEEE MTT-S International Microwave Workshop Series on Innovative Wireless Power Transmission: Technologies, Systems, and Applications, 2011, pp. 3-6, doi: 10.1109/IMWS.2011.5877137.
59. V. Khare, P. Chaturvedi, and M. Mishra, «Solar energy system concept change from trending technology: A comprehensive review», e-Prime - Advances in Electrical Engineering, Electronics and Energy, vol. 4, p. 100183, 2023, doi: 10.1016/j.prime.2023.100183.
60. L. S. Mason, «A solar dynamic power option for space solar power», SAE Technical Paper Series, 1999, doi: 10.4271/1999-01-2601.
61. S. Sasaki, K. Tanaka, and K.-I. Maki, «Microwave power transmission technologies for solar power satellites», Proceedings of the IEEE, vol. 101, no. 6, pp. 1438-1447, 2013, doi: 10.1109/JPROC.2013.2246851.
62. J. M. Osepchuk, «How safe are microwaves and solar power from space?», IEEE Microwave Magazine, vol. 3, no. 4, pp. 58-64, 2002, doi: 10.1109/MMW.2002.1145676.
63. P. Jaffe et al., «Sandwich module prototype progress for space solar power», Acta Astronautica, vol. 94, no. 2, pp. 662-671, Feb. 2014, doi: 10.1016/j.actaastro.2013.08.012.
64. J. Bucknell, «Survey of Space-Based Solar Power (SBSP)», 2024.
65. J. C. Mankins, «New developments in space solar power», NSS Space Settlement Journal, pp. 1–30, 2017.
66. X. Meng, C. Liu, X. Bai, K. Du, C. F. A. López, J. C. Mankins, H. Baig, and T. K. Mallick, «Optical study of a cocktail structural Space-based Solar Power Station», Solar Energy, vol. 194, pp. 156-166, Dec. 2019, doi: 10.1016/j.solener.2019.10.053.
67. H. Barde, «A Skeptic's Take on Beaming Power to Earth from Space», IEEE Spectrum, May 2024. [Online]. Available: https://www.ieee.org/spectrum.
68. I. Cash, «CASSIOPeiA solar power satellite», in 2017 IEEE International Conference on Wireless for Space and Extreme Environments (WiSEE), Montreal, QC, Canada, 2017, pp. 144-149, doi: 10.1109/WiSEE.2017.8124908.