**FMIF20 - Miljöfrågor i ett internationellt perspektiv**

**Assignment 2 - Final Paper**

# Could space-based solar power systems replace ground-based photovoltaics?

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# Abstract

In light of the ongoing debate surrounding the sustainability of current energy sources, this paper investigates the potential of space-based solar power (SBSP) systems as an alternative to ground-based solar power (GBSP) systems. The study aims to determine whether SBSP can provide a reliable and large-scale solution that considers sustainability and environmental-friendliness while addressing the challenges its implementation may face compared to existing GBSP systems. Additionally, the paper analyzes the potential power input to the grid from this new renewable source of energy, the economic aspect of the SBSP satellite installation and the economical constraints related to the installation of a rectifying antenna (rectenna), required for wireless energy transmission from space. Policy support is also discussed for the future development of SBSP. Through this comparative analysis, the study offers key insights into the potential for SBSP to replace GBSP, concluding if GBSP can or could be a viable addition to the global energy mix in the global transition to renewable energy.

**Keywords**: Space-Based Solar Power, Ground-Based Solar Power, Solar PV, Renewable Energy

# INDEX

# 1. Introduction

The rise of global climate challenges and energy demands calls for increasing deployment of renewables such as solar and wind to replace fossil fuels. Ground-based solar power (GBSP) systems have been widely adopted as an environmentally friendly energy solution. However, the intermittency of power output and the high occupation of land pose challenges to scaling GBSP systems sufficiently to achieve the zero CO2 emissions target. In response, space-based solar power (SBSP) technology has emerged as a potential alternative that offers continuous, large-scale energy production with high land-use efficiency (Dotson, Eddy, & Swan, 2022).

An SBSP system can harness sunlight through solar collectors positioned in orbit, convert the energy through microwave or laser transmitters, and direct it to Earth, which is received by a ground station that converts the microwave or laser transmission into electrical power flowing into the power grid. Unstable weather conditions and day/night cycles that affect the performance of GBSP significantly would have minimal impact on the SBSP system (Dotson, Eddy, & Swan, 2022). However, the barrier of high costs and emissions from rocket-based launch make it unclear whether SBSP would be a competitive option. This study explores whether SBSP systems could replace or complement current ground-based solar power systems, focusing on technological maturity, environmental impacts, economic feasibility, and policy support.

This research aims to answer several key questions: Is SBSP a viable and more sustainable option than existing GBSP systems? What are the potential environmental benefits or limitations of space-based solar power systems compared to GBSP systems? How would the energy efficiency of SBSP influence global renewable energy targets? Is it economically feasible, and what policy support is there for its future development?

To answer these questions, we first review ground-based solar power technology and introduce the concept and development of space-based solar power technology. Then, we present a comparative analysis of the power output, environmental impact, technological and economic considerations, and policy support of space-based solar power systems relative to ground-based systems. Through this comprehensive discussion, we evaluate if orbital power can deliver consistent energy output on a large scale, addressing the question of sustainability by evaluating its long-term environmental impact (CO2 emissions, land occupation, and ecological effects) and ability to operate without exhausting resources. We aim to clarify SBSP's potential role as a reliable, efficient, and sustainable alternative to the current terrestrial energy sources.

# 2. Methodology

## 2.1 Literature Research

To classify our research and our references we first identified keywords like Space-based solar power (SBSP), SBSP projects, Photovoltaic systems (PV) or solar panels. Moreover, a selection of papers that were published in the last fifteen years was done in order to be as accurate as possible with the data offered and technological advances made.

The data bases used to get all the information were mainly Google Scholar and references from other papers that we were also reading.

Also, we focused on projects such as the SOLARIS, a project conducted by the European Space Agency (ESA); the SPS_ALPHA, conducted by NASA; and Caltech´s Space Solar Power Demonstrator.

## 2.2 Comparative Analysis

In this work, Space-Based Solar Power (SBSP) and Ground-Based Solar Power (GBSP) systems are evaluated using a thorough comparative method. Potential for energy generation, lifecycle emissions, land use, environmental effects, and economic viability are some of the important factors examined. The performance of GBSP is examined in light of its reliance on atmospheric and terrestrial restrictions, whereas SBSP is evaluated for its capacity to deliver power continuously. Aspects including lifecycle emissions, land efficiency, and energy generation are quantified using numerical computations.

Estimates of greenhouse gas emissions from the production, transportation, operation, and disposal phases are included in the analysis. To illustrate efficiency disparities, energy density calculations and land occupation measures are also carried out. To guarantee accuracy and dependability, data from reputable sources such as space agencies and energy organizations are combined, providing a strong foundation for assessing these technologies.

# 3. Theory

## 3.1 Current solar power generation

Solar energy is the most abundant energy source available on the planet, having a $1.8 \times 10^8$ MW of power hitting the earth's surface. For this reason, there is a large potential in this kind of energy source. GBSP systems are the best technology to date to convert the sun's energy into electrical energy, and the one with the least environmental impacts, especially compared with the most common energy source worldwide, fossil fuels. There have been big improvements over the years in the GBSP technology and as time goes on, more and more photovoltaic power plants are installed. According to

*Our World in Data* the annual solar production worldwide is about 1629 TWh. This technology is one of the most important renewable energy production technologies, constituting around 5.5% of total energy production and around 18.2% of total energy production from renewable sources. Some countries, due to their geographic positioning have larger investments in solar power plants, while others might have to consider other renewable energy sources. However, like all technologies, GBSP has some limitations and environmental impact, such as production emissions, waste and depending on the area where these power plants are installed, there could also be some risks regarding deforestation and destruction of current ecosystems when trying to install as many solar plants as possible.

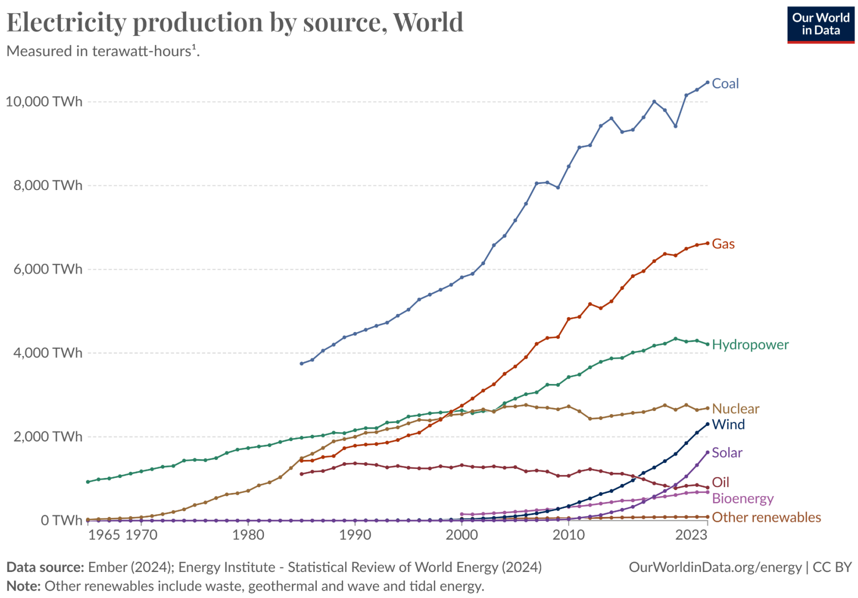



*Figure 1 - World Electricity Production by Source*

Solar photovoltaic panels work based on the photovoltaic effect, converting the energy from the sun (light) directly to electrical energy. This technology uses semiconductors' material properties to convert light energy. By shining light on a semi conductor, the radiation will excite valence electrons into the conduction layer, where they are free to move, producing electrical energy.

Photovoltaic modules have had a lot of development over the years, and new technologies have surfaced with time, being the main ones Monocrystalline, Polycrystalline and Thin film solar cells, with efficiencies of 14%-17.5%, 12%-14%, and 16%-17% respectively. To make the solar panels perform at their maximum efficiency some working requirements must be fulfilled. A temperature of operation around 25ºC is crucial, since that for each 1ºC increment the output drops by 0.4–0.5%. Furthermore, investments in solar tracking systems improve the overall efficiency of the solar panel, allowing it to have an optimal orientation in reference to the sun's position.

## 3.2 Concept and Development of Space-Based Solar Power

SBSP can take many forms and designs, and is a technology being researched by different regions like the USA, Japan and the EU with the goal of reaching net zero emissions and achieving energy independence and continuous power generation. This technology is based on the concept of creating a satellite system that could collect radiation from the sun, converting it to electrical energy. Then, converting this energy into microwaves or lasers, depending on the design of the Wireless Power Transmission, the energy could be sent to Earth where an antenna could receive the power and supply it to the electrical distribution grid.

NASA has been one of the main participants in the development of SBSP using a Microwave Wireless Power Transmission, and has designed two technologies that could be fully implemented by 2085. One of the designs is the Innovative Heliostat Swarm Concept, which consists of a system of multiple hexagonal solar panels that cover an area of 11.5 km2. The second design is the , which consists of 5 systems of standard solar panels, covering an area of about 19 km2. Depending on which design for the satellite is implemented, the size of the ratifying antenna is different, where a Innovative Heliostat Swarm Concept requires a larger antenna, since the satellite has a larger area compared to the Mature Planar Array Concept (which has 5 satellites of 3.8 km2 each).

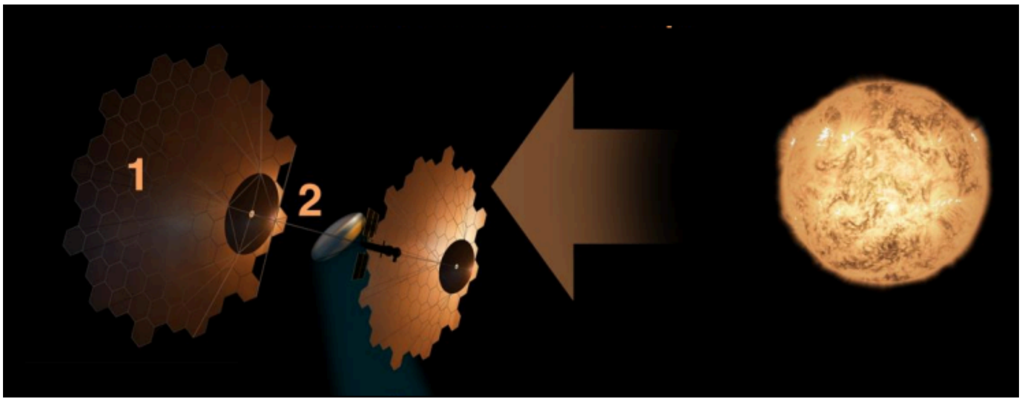



*Figure 2 - Innovative Heliostat Swarm Concept*

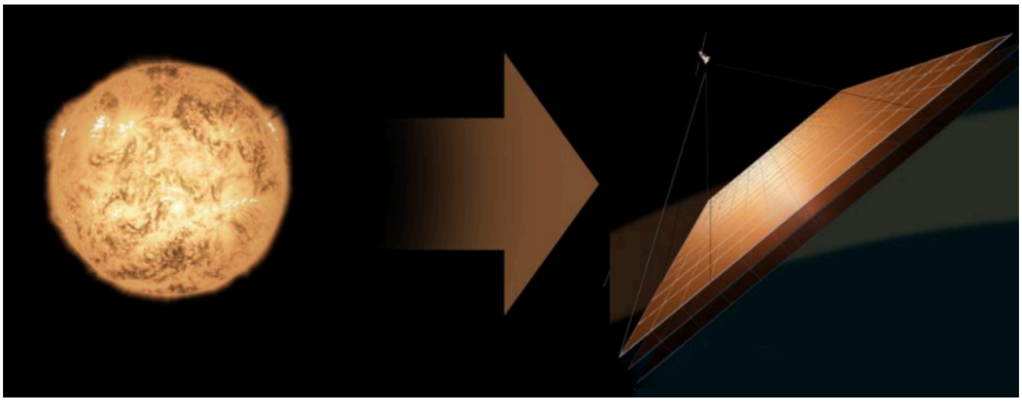


*Figure 3 - Mature Planar Array Concept*

The European Space Agency is also investing in research to explore the feasibility of this technology, creating an initiative called Solaris. With the help of Thales Alenia, the ESA should be concluding if Solaris is a feasible option by 2025.

These were just two examples of recent SBSP investments, but there are even more designs dating back to 1973, where Peter Glaser created one of the first theoretical designs.

# 4. Results and Discussion

## 4.1 Power output from SSPS (Space Solar Power Satellite)

A space solar power satellite would allow us to collect energy from the Sun 24 a day, every day, something that current GBSP systems are very limited to, which is the main reason why they aren't a direct solution to the transition to renewable energy. With this constant power output, the energy demand would be aligned with the energy supply, making it a reliable renewable energy source. Another advantage of SSPS is that it works in a vacuum medium, which means that there is little attenuation of the solar radiation, making it a more efficient process. Furthermore, by working in a vacuum there is no erosion and oxidation caused by the atmosphere and climate conditions, extending vastly the life of the satellite. Lastly, a reason why some countries are investing in the development of this technology is because SBSP gives energy security through a renewable source. Having a constant power supply means that even in times when the Earth's resources might be scarce, a safety guard allows for the country's stability.

Since there is limited data on the subject a comparison between current solar production and SBSP will be made using the USA as an example, using data from NASA, the U.S Department of Energy and Our World In Data.

The Innovative Heliostat Swarm Concept would supply 2GW to Earth, and considering it would work constantly throughout the year this would equate to 17TW.h of yearly energy.

$$yearly\ energy\ supplied\ =\ 2GW \cdot 365\ days \cdot 24\ hours\ =\ 17,52\ TW.h$$

The land necessary to install an antenna that can receive the energy from the SSPS (which is the component that occupies the biggest share of land) should be around 500 km in diameter, giving a total of 0.00112 km2 of land used per GW.h. Comparing it with current GBSP farms in the USA, which is 1.13 km2 of land per GW.h, we can see that SBSP is 3 orders of magnitude more energy dense than standard solar PVs.

$$land\ used\ by\ the\ antenna = \pi r^2 =\ 20\ km^2$$

$$area\ of\ land\ needed\ per\ GW.h = \frac{20\ km^2}{17\ 520\ GW.h} = 0.00112\ km^2/GW.h$$

When looking at solar panel area per GW.h in both technologies there is also a difference of 3 orders of magnitude, being the SBSP solar panel area per GW.h equal to 0.000656 km2 / GW.h and for GBSP equal to 0.81 km2 / GW.h. This means that not only do we need less land to produce the same amount of energy in relation to current solar panel farms, but also we need substantially less solar panels to produce the same amount.

$$solar\ panel\ area\ needed\ per\ GW.h = \frac{11.5\ km^2}{17\ 520\ GW.h} = 0.000656\ km^2/GW.h$$

Even thou[illegible]ing the energy demand in most developed countries, it doesn't seem to supply enough electricity to compete with other energy sources. Figure 4 represents the energy demand of different countries, which shows that the USA consumed around 4266TW.h in 2023, 250 times more than the SBSP NASA design could provide. Comparing this technology to current solar power plants, which account for 5.6% of energy production in the USA, and 236TW.h in 2023, there would have to be around 13 SBSP power plants to replace all GBSP power plants. Moreover, considering that SBSP is not cost competitive, which will be discussed later, this technology can not compete with current GBSP power plants.

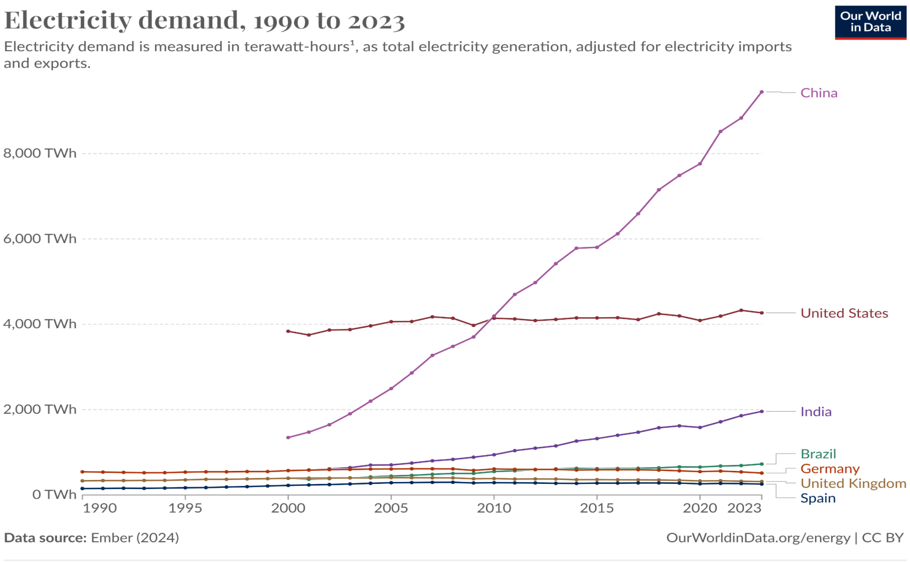



*Figure 4 - Electricity Demand in Different Countries*

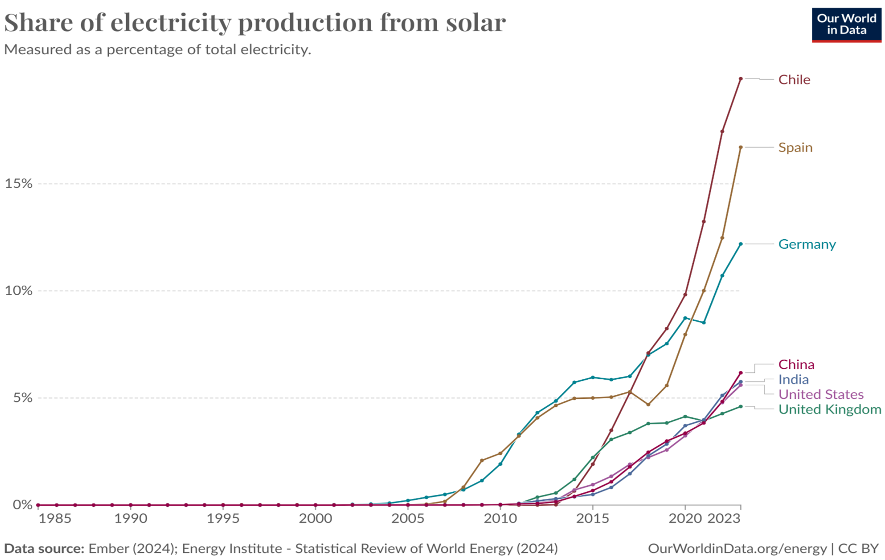



*Figure 5 - Share of electricity production from solar in each country*

## 4.2 Environmental Impact

### 4.2.1 $CO_2$ Emissions

Greenhouse gas (GHG) emissions of SBSP systems and GBSP systems are quite different in terms of the stage of GHG creation. Therefore, a comparison considering their whole life cycles is necessary. SBSP has high emissions during manufacturing and transportation and unique challenges during installation and disposal, while emissions of GBSP systems mainly come from the manufacturing of PV modules.

**1. Manufacturing Stage**

For GBSP, the infrastructure phase contributes to the most greenhouse gas emissions of its life cycle, ranging from 93% to 99.9%, of which the production of materials exhibits the most (Bošnjaković et al., 2023). While GBSP focuses on solar cells and structure design to harness energy from the ground, SBSP requires high-performance materials and precise manufacturing operations for spacecraft, servicers, launch vehicles and ground support infrastructure to be well prepared for the harsh space environment, resulting in higher energy consumption and carbon emissions. However, recent studies, including those by ESA in 2023, also show that SBSP systems require significantly less material (solar panels) to produce a certain amount of energy than GBSP. The overall material efficiency compensates for some of the emissions from manufacturing processes and potentially leads to a lower overall carbon footprint over the system's life cycle (Kang et al., 2024). To increase the environmental-friendliness of SBSP, further research to promote the selection of environmentally friendly and recyclable materials and the development of efficient manufacturing processes are necessary.

**2. Transportation Stage**

Transportation is the largest contributor to the GHG emissions of the entire SBSP's life cycle. In this stage, SBSP components manufactured on Earth should be transported into space, and the energy-intensive rocket launching processes can consume a large amount of fuel and release significant amounts of $CO_2$ and other pollutants. According to NASA's study, the thousands of launches required can account for 64-72% of total emissions across the SBSP lifecycle (Rodgers et al., 2024, p. 14). Therefore, increasing transportation efficiency is necessary to reduce the carbon emissions of SBSP.

**3. Installation Stage and Operational Stage**

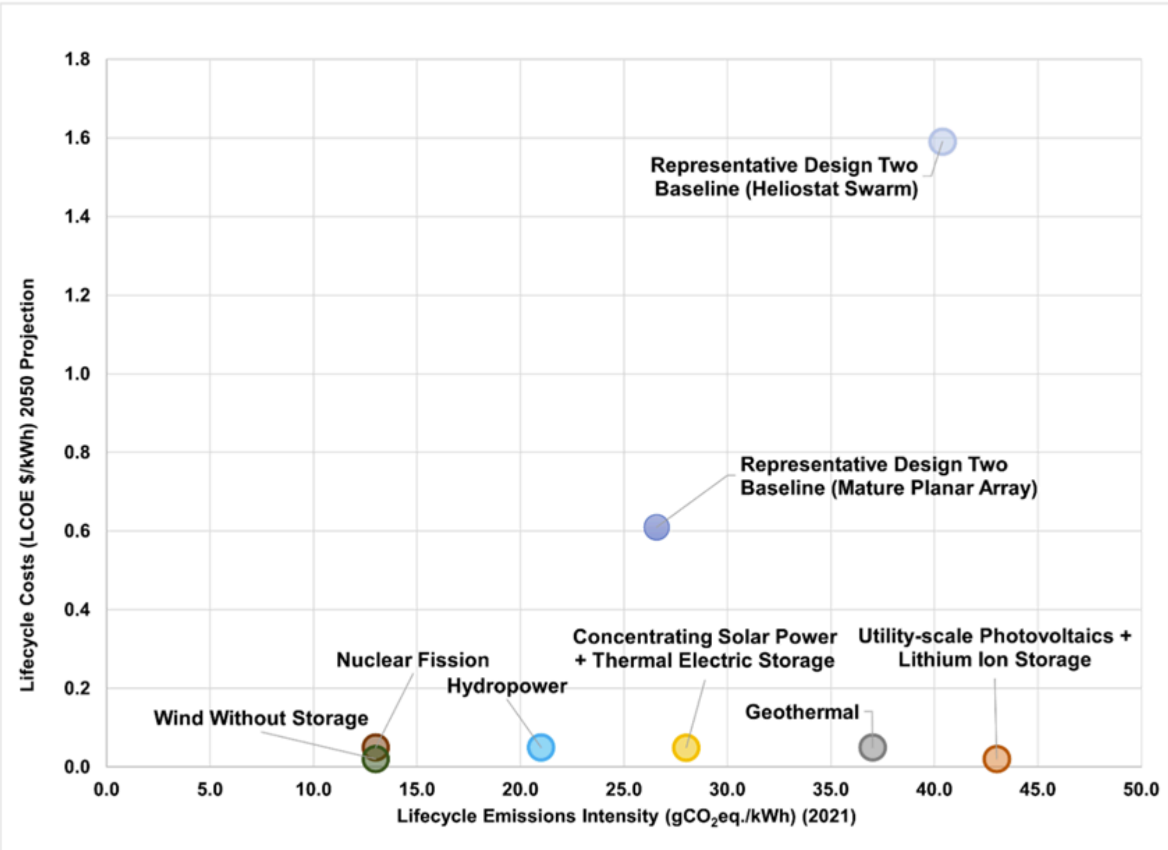
Different from the ground installation of GBSP, the installation of SBSP involves assembling complex components in extreme space conditions, which may cause more resource consumption and, therefore, more emissions. However, SBSP has the advantage of providing continuous, stable energy for a longer period, which can compensate for the emissions from the initial installation (Kang et al., 2024). As is the case of operation, maintenance activities for SBSP can be more complicated and may require additional launches and materials that can cause significant ongoing environmental impacts (Rodgers et al., 2024).

**4. Disposal and Recycling Stage**

While well-established procedures exist for disposing of and recycling GBSP panels to minimize the end-of-life impacts, dismantling and recycling SBSP systems in space remains a largely unresolved challenge. Efforts in technical innovation, including recovery of recyclable resources and disposal methods, and related policies for the efficient end-of-life management of an SBSP need to be made to reduce the long-term environmental impacts (Kang et al., 2024).

NASA conducted a lifecycle study of two representative SBSP designs that are presumed to start operating in 2050 for 2 GW utility-scale power generation. It used a hybrid mass and spend-based Economic Input Output-Life Cycle Analysis (EIO-LCA) approach, combining material decomposition with authoritative sources on the emissions intensity of delivering components and materials and accounting for emissions across Develop, Assemble, Operate, Maintain, and Dispose phases. The results for the two designed SBSP systems are 26 gCO2eq./kWh and 40 gCO2eq./kWh (Rodgers et al., 2024). For comparison, according to NREL's Lifecycle Assessment Harmonization effort, which documents the range of assessed GHG emissions, the low, medium, and high impact values for ground-based utility-scale solar photovoltaics are 25, 43, and 190 gCO2eq./kWh respectively (National Renewable Energy Laboratory, 2023). Those results indicate that SBSP and GBSP have similar lifecycle GHG emissions intensities, both offering significant advantages over fossil fuels. For reference, the median GHG emissions intensities of coal and natural gas electricity generation are 486 gCO2eq./kWh and 1001 gCO2eq./kWh respectively (National Renewable Energy Laboratory, 2023).

Figure 6 - SBSP Systems (Baseline) and Other Renewables




In conclusion, although SBSP can bring about higher emissions during the manufacturing and transportation stages, its enhanced material efficiency and extended operational lifespan may lead to a reduced overall environmental footprint compared to GBSP. While SBSP demonstrates potential for providing a stable and sustainable power supply, it remains in its early development phase. To unlock its potential, further research on sustainable strategies must target emission reductions across all lifecycle stages, from improving manufacturing processes to enabling eco-friendly disposal. Advances in energy-efficient manufacturing, transportation technologies, and recycling innovations would be essential for maximizing SBSP's contribution to a sustainable energy future.

### 4.2.2 Land Occupation and Ecological Impact

Land use refers to the extent and type of land occupied by GBSP power plants, which can influence natural habitats and biodiversity. For GBSP, distributed PV installations designed to integrate with existing structures such as rooftops have relatively low environmental impact. At the same time, large-scale solar farms often require clearing or grading large areas, which can fragment or displace natural habitats (Bošnjaković et al., 2023). For SBSP systems, the rectifying antennas needed to receive microwave beams carrying solar power generated in space are significantly less invasive compared to GBSP's utility-scale solar farms, can often coexist with other uses of the land or sea on which they will be built, such as agriculture, reducing disruptions to natural ecosystems (Pultarova, 2022). Furthermore, while the flexibility of rectenna facilities allows for avoiding sensitive ecological zones, GBSP systems often cause intensified land conversion, such as deforestation, in the deployed areas (Turney & Fthenakis, 2011).

For GBSP, ecological risks are more localized, including habitat fragmentation, soil degradation, microclimate changes, and water usage issues during the construction and operation of large-scale solar farms (Turney & Fthenakis, 2011). While SBSP can lower direct terrestrial ecological disturbances, new challenges arise due to its reliance on wireless transmission and launch activities. Studies highlight that electromagnetic interference may disrupt the internal magnetic compasses of migratory birds and cause navigation problems (Morrison, 2014). The emissions produced by rocket launches can contribute to atmospheric changes, including potential ozone depletion (Ross et al., 2010). The generation of space debris is another concern for potential harm to ecosystems, and responsible space debris management strategies are crucial for ensuring the sustainability of SBSP systems (Green.org, 2024).

In conclusion, while the more established GBSP systems face ongoing challenges related to high land demand and the associated ecological impacts, SBSP offers significant advantages in minimizing land occupation and direct terrestrial ecosystem disruption. However, new environmental challenges, including space debris management and electromagnetic risks, may appear and call for further study and mitigation strategies.

## 4.3 Technological and Economic Considerations

Collecting solar energy in space would theoretically provide a continuous and weather-independent energy source. However, some aspects need to be assessed to determine whether it is a viable resource and if it is feasible technologically and economically.

### 4.3.1. Technological maturity

Space-based solar power (SBSP) systems have the advantage that they would not be affected by the atmosphere and could provide continuous and uninterrupted power, mainly because they would receive continuous sunlight. They would be a very effective energy source compared to GBSP systems, as these can only generate power when the conditions are optimal, only during daytime, and only when there is enough sunlight. While current GBSP technology is constantly improving and is increasing its effectiveness, the only way to overcome the environmental limitations is to take this technology outside the atmosphere. Current investigations show promising results in efficiency and durability under intense radiation conditions making SBSP more feasible. Companies such as NASA and ESA are investing in materials that can resist these critical conditions, which are essential to producing energy in the long term. Although these technologies have been constantly improving in the last decades, they are still in development and a lot of work has still to be done to make SBSP as efficient as GBSP systems, and some more to make them better.

Moreover, one of the main technological problems encountered is wireless power transmission which has to be implemented to transmit energy from space to Earth (Caltech Space Solar Power Project). As explained before, this would be done by converting energy to microwaves or laser beams. Small-scale tests, such as those conducted by Caltech (Than, 2023), show progress; however, they have encountered safety issues and efficiency losses over long distances as well as other problems. This makes it impossible to use the technology right now. A lot of research and innovation must be done to make it apt for use…

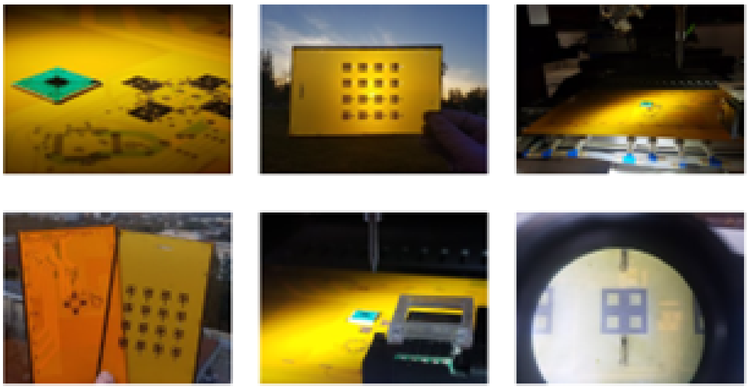


*Figure 7 - Caltech´s wireless power transfer systems*

Furthermore, its assembly and maintenance must be taken into account. SBSP requires extensive work on these, which is also complicated because of their location in orbit. Both NASA´s On-orbit Servicing, Assembly (NASA, 2024) , and Manufacturing (OSAM) and ESA´s SOLARIS project (ESA, 2023) are making advancements in robots for in-space assembly. This is a huge achievement, however, for now, autonomous construction is not reliable enough to implement SBSP as an alternative energy source to GBSP systems.

In summary, talking about the technological aspects of SBSP, in the near future this technology will not be implemented. The improvements and innovations being made make it an up-and-coming technology, but it still has to be improved to rely on it as a power source. Also, this technology will be a complementary source of energy rather than a replacement for GBSP systems. For now, GBSP remains a more viable alternative for large-scale renewable energy, but SBSP could eventually serve specific high-demand or remote applications, especially those who need energy 24/7, some examples could be the healthcare sector, as hospitals need to rely on a constant source of energy or the military.

| | SBSP (Space-Based Solar Power) | GBSP (Ground-Based Solar Power) |
|---|---|---|
| ✅ Advantages | - **24/7 Energy Production:** Independent of weather and day/night cycles.<br>- **High Efficiency in Space:** Operates in a vacuum without atmospheric interference. | - **Proven Technology:** Mature and reliable.<br>- **Easy Maintenance:** Simple to install, maintain, and scale.<br>-**Continuous Improvements:** Ongoing advancements in efficiency and scalability. |
| ⚠️ Challenges / Limitations | - **Wireless Power Transmission:**<br>- Efficiency loss over long distances.<br>- Safety concerns (radiation/interference).<br>- **Complex Assembly & Maintenance:** Requires robotic systems (e.g., NASA OSAM, ESA SOLARIS).<br>-High costs for orbital repairs. | - **Intermittent Supply:** Weather and day/night cycles affect performance.<br>- **High Land Use:** Requires large areas for utility-scale plants. |

*Table 1 - Summary of technological feasibility*

### 4.3.2. Costs and economic feasibility

To establish whether implementing SBSP as an energy source is economically feasible some factors such as the capital costs, the operational and maintenance costs, and the price per kWh, must be considered.

Firstly, there is a difference between the initial investment that has to be made to use SBSP and GBSP systems. SBSP systems require a much bigger investment. For instance, just the cost of launching all the necessary equipment into orbit and setting up the SBSP system would ascent to billions of dollars. Even though advancements are being made to reduce these costs such as reusable rocket technology, powered by SpaceX, the upfront costs are still way above those of GBSP.

Furthermore, SBSP systems require some maintenance to ensure optimal performance. Due to the on-orbit maintenance requirements and the current technology, the cost of SBSP systems maintenance, in the long run, is significantly higher than GBSP systems maintenance. This is because the technology to repair terrestrial systems is already accessible and does not require remote repair systems.

To provide a better understanding of the economic feasibility of SBSP systems compared to GBSP systems, Figure 8 has been created. This figure compares the key cost components of both technologies, including overnight capital costs, annual operational and maintenance (O&M) costs, and 30-year cumulative O&M costs for a 1 GW capacity system. It highlights the stark differences in investment and operational expenses, offering a visual representation to support the discussion on the economic challenges and potential of SBSP relative to GBSP systems. (Jeffrey L. Caton Mr., 2015)

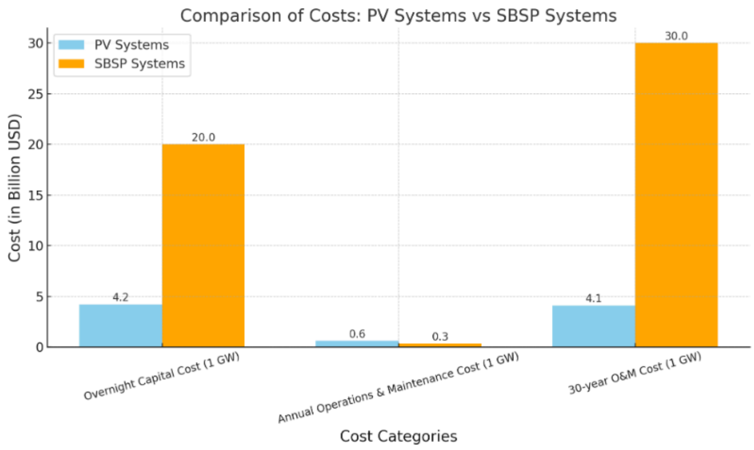



*Figure 8 - Cost Comparison between GBSP and SBSP*

In conclusion, the technology behind space-based solar power (SBSP) must undergo significant advancements and progress at a rapid pace to become economically viable. Currently, the economic feasibility of SBSP remains limited, and given the substantial upfront costs and uncertain return on investment, it is unlikely that investors would allocate capital to such projects without a clear prospect of financial return. Therefore, further technological innovations and cost reductions are essential for SBSP to become a commercially viable energy solution.

## 4.4 Policy Support

As we move  toward 2030, various nations have started expressing keen interest in finding breakthroughs in how to generate energy sustainably. In  this background, SBSP has received a interest with its 24 by 7 generation of baseload energy, and its placed itself in a really good place on the route to creating sustainable power. “While national and regional policies  or initiatives are being made as they begin to recognize the potential of the SBSP, there are many areas for improvements in regulatory frameworks

### Regional and National Policy:

As we move toward 2030, various nations have started expressing keen interest in finding breakthroughs in how to generate energy sustainably. In this background, SBSP has received a interest with its 24 by 7 generation of baseload energy, and its placed itself in a really good place on the route to creating sustainable power. “While national and regional policies  or initiatives are being made as they begin to recognize the potential of the SBSP, there are many areas for improvements in regulatory frameworks

With countries such as UK trying to develop the SBSP, the government has already partnered with private companies such as Space Solar. Space Solar's initiatives correspond perfectly with the government's steps towards decreasing energy dependency. In 2022, the European Space Agency (ESA) approved  the SOLARIS program. The long-term vision of the program is that by 2050,  SBSP be part of Europe’s energy mix. This program also examines how SBSP can support Europe’s net zero carbon emissions strategies. SOLARIS is aimed at technology development, risk assessment and economic evaluation (ESA, 17 April 2023).

Japan has emerged as a leader in SBSP research and development in Asia. There are several experiments that Japan has been conducting on wireless energy transmission via the Japanese Aerospace Exploration Agency (JAXA), Paek, S. W., Kneib, J. P., & de Weck, O. (2015). japan also plans to carry out SBSP technology Full-scale development. The above initiatives from the respective countries demonstrate the commitment by the countries towards the transition to renewable energy and also at the same time sets up SBSP as a part of future.

In conclusion the future of SBSP will be greatly influenced by regional policies and activities, with the UK, and Japan spearheading creative endeavors. These pledges, along with the help of international cooperation and technology developments, establish SBSP as a critical step in the direction of global energy sustainability.

# 5. Conclusion

This study offers a comparative analysis on SBSP and GBSP highlighting the opportunities in SBSP and its challenges. The main strength of SBSP is its energy supply, since it can offer continuous large amounts of power to Earth, making it a reliable source of energy, which is not the case for GBSP. Furthermore, the exponential reduction in area needed to operate SBSP reduces the potential deforestation of large fields done to install traditional solar panels, making it a far more environmentally friendly solution.

However, some limitations remain, such as high initial costs, technological immaturity and launch emissions. These constraints can decrease with time, as technology becomes more mature costs decrease making it possible for the future to be a viable technology. GBSP remains the best choice when considering this alternative, even being limited by its intermittent energy supply, it is still a more cost effective and scalable solution with an already important role in worldly energy production.

This study is limited by the amount of information regarding this innovative and not implemented technology. Not many agencies are exploring this technology, and most of the relevant data around it is either private or purely theoretical.. The use of less precise and abstract measures was necessary due to the lack of development in this field, and rough estimates were the best the study could attain. It is necessary to further investigate and develop SBSP technology in order to truly understand its role in the global energy picture.

# 6. Future Prospects

The future of space-based solar power is bright, with its advancements in technology, policy support, and innovative applications, which ultimately drive us toward the transformation of sustainable energy.

### Technological Advancements:

All technology to implement SBSP is already available, but different components have different levels of maturity. The photovoltaic panels that would be placed on the satellite are a very developed technology, which doesn't require more improvements to make the project viable. However other segments of SBSP are still in the early stages of their development, such as reusable rocket technology first accomplished by SpaceX with the Falcon 9 rocket, and also wireless power transmission systems that recently started being applied in a small scale as a charging method for electric vehicles and mobile phones. Advancements in technology are crucial factors for the SBSP to sustain for long. Key areas to focus on are reusable rocket technology, energy transmission systems, and in-space robotic assembly. A technological innovation regarding the robot assembly called as gigafactories, which include robotic systems for manufacturing and assembly, thereby reducing human involvement (Paek, Kneib, & de Weck, 2021).

### Resource utilization:

The depletion of resources and energy needed to extract these resources are the major concerns in the current world scenario. Therefore, it becomes necessary to choose a hybrid approach to the utilization of resources. Combined utilization of earth-based resources with lunar-based resources seems to be the right path to counteract the logistical challenges associated with large-scale SBSP systems (Paek, Kneib, & de Weck, 2021).

### Energy transmission systems:

Companies like Space Solar are trying to explore energy transmission systems, which include beaming energy to mobile assets and across regions without any need of extensive transmission infrastructure. Space Solar's mission is to deliver a 30 MW system within six years that will provide commercial power to energy-intensive sectors such as data centers, mining, and maritime operations (Space solar, 2024). To improve scalability and preserve operational redundancy, distributed SBSP systems such as swarms of smaller satellites are advised. This strategy reduces the danger of individual satellite failures. (Rodgers et al., 2024).

### Economic Viability:

Focusing on the economic viability of SBSP paves the way for a more sustainable and economically robust energy future. According to experts, SBSP can draw in investments and cut expenses by utilizing synergies from the space economy, such as asteroid mining and space exploration (Dotson, Eddy, & Swan, 2022).

In conclusion, Space-based solar power offers a sustainable future, driven by technological advancements, resource integration, and innovative applications. It can make a key impact on energy generation and meet global energy challenges. The path to SBSP is an important milestone towards a sustainable future.

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