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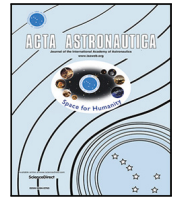
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Research Paper

Orbital capacity and maximum energy output of a space-based solar power constellation in Geosynchronous Earth Orbit

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ABSTRACT

As the global demand for sustainable energy solutions intensifies, the spotlight turns to innovative technologies, with Space-Based Solar Power (SBSP) emerging as a promising route. The aim of this paper is to achieve, to the best of the authors' knowledge, the first global assessment of the maximum energy output of a network of Space-Based Solar Power stations in Earth's orbit.

First, several baseline architectures are selected based on existing literature related to Geosynchronous Earth Orbit, with a focus on key mission and system designs, as well as the expected performance of each. Second, considering the unique characteristics of these architectures, the maximum orbital capacity for a Space-Based Solar Power constellation is determined in increasingly stringent scenarios. Finally, an annual maximum energy output is evaluated for each scenario, using a power generation model, and compared against recent global energy demands.

The proposed study aims at establishing a framework for the evaluation of the potential energy output achievable for planet Earth through Space-Based Solar Power systems. This will enable comparison of Space-Based Solar Power with other renewable energy systems and foster further research and discussions on this promising technology.

1. Introduction

The global pursuit of sustainable energy solutions has led to increased interest in innovative technologies capable of providing consistent and renewable power. Among these emerging technologies, Space-Based Solar Power (SBSP) stands out for its ability to consistently capture the Sun's energy, almost unaffected by the day-night cycle, while achieving significantly greater efficiency than Earth-based solar collection. In this respect, this work aims to conduct the first comprehensive global assessment of the maximum power output achievable by a constellation of SBSP stations in geosynchronous Earth Orbit (GEO). Drawing methodological inspiration from the work of Archer et al. [1], this study proposes a structured approach to assess the potential of SBSP systems.

Although many activities have focused on the technical feasibility and economic viability of specific SBSP concepts, there is a critical need for standardized criteria to systematically assess and compare these

concepts. Therefore, this research aims to fill this need by analyzing how different scenarios impact the overall energy output of an SBSP constellation.

This paper begins with a general overview of the most popular SBSP concepts proposed over the years. These include designs from SPS-ALPHA (USA) [2,3], CASSIOPEIA" (UKSA-ESA) [4], Thales Alenia Space Concept (Italy-France) [5], MR-SPS (China) [6], and K-SSPS (Korea) [7]. Each concept is analyzed in terms of its proposed power output, technological innovations, and orbital regime considerations. Furthermore, the rated power to the grid is considered, and the maximum number of stations that can populate the Geosynchronous Earth Orbit is evaluated. A preliminary evaluation treats Earth as a giant receiving antenna, assessing the spatial distribution and potential interference among stations.

Next, the current population of active satellites and other orbital objects is taken into account. SBSP stations are then placed in the

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GEO orbit with a minimum angular separation to avoid interference among SBSP stations and between SBSP stations and existing satellites. The number of stations that can be placed varies according to the minimum angle set. The study then evaluates the ground segment, determining which longitudes can host a ground station, also considering the availability of energy distribution infrastructures. Using the European Space Agency (ESA) World Cover data [8], the study cross-checks the available longitudes with orbital analysis to produce more reliable results. The analysis is further refined by focusing on areas with a higher population density, as these regions are supposed to have the necessary infrastructure, such as electrical energy distribution lines, to support the SBSP ground segment. Finally, an estimate of the total power output is made based on the maximum number of stations that can be deployed and a dedicated proposed model. This output is then compared with the world yearly electricity consumption data, providing a comprehensive assessment of the SBSP potential contribution to the global energy production.

2. State of the art on SBSP systems

2.1. SBSP origins

Peter E. Glaser first proposed the idea of harnessing solar energy from space. In his seminal paper of 1969 [9], Glaser outlined a vision where large solar power satellites in GEO orbit would continuously collect solar energy, unaffected by the limitations of terrestrial solar power systems, such as the day and night cycle, and the cloud coverage. The solar energy would be converted into microwave radiation and transmitted to Earth, where it would be captured by large antenna arrays, or *rectennas* [10], and converted back into electricity. Furthermore, the 1974 “Feasibility Study of a Satellite Solar Power Station” [11], examined the technical and economic viability of constructing and operating such an SBSP system. This was followed by the 1976 “Space-Based Solar Power Conversion and Delivery Systems Study” [12], which focused on the technological challenges of converting solar energy into microwaves and efficiently transmitting it to Earth. By 1979, the “Earth Benefits of Solar Power Satellites” [13] study highlighted the potential environmental and economic benefits of SBSP stations, particularly in reducing greenhouse gas emissions and mitigating the geopolitical risks associated with fossil fuel dependency. Glaser’s early designs envisioned SBSP satellite systems of very large size, with solar arrays spanning several kilometers and an estimated weight of tens of thousands of kilograms. These satellites were estimated to generate between 5 to 10 gigawatts of continuous power. The challenges identified in the early studies, such as the environmental impact of microwave transmission and the technological difficulties of building large structures in space, continue to be relevant today.

2.2. Global framework

The resurgence of interest in Space-Based Solar Power can be traced back to the late 1990s, marked by a renewed focus on the potential of harvesting solar energy in space for transmission to Earth. A key milestone occurred in 1997 with the publication of pivotal research that re-examined the viability of Solar Power Satellites (SPS) as a solution to growing global energy demands. Primarily conducted by J.C. Mankins, this “Fresh Look” study [14] evaluated different concepts, revisiting earlier designs from the 1970s while considering more advanced technologies available.

This exploration spurred further research, leading to the publication of another significant study in 2002 [15] and 2003 [16]. This researches emphasized the complexity of future large-scale SBSP systems, highlighting the need for incremental technological advancements. Although many technological challenges remained, progress in areas like microwave power transmission and efficiency improvements for components such as rectennas demonstrated the potential feasibility of

SBSP. The study outlined the need for a strategic roadmap to ensure that each technological advancement would offer broader applications beyond SBSP. In addition, the publication of “The Case for Space-Based Solar Power” [17] laid the foundation for an ongoing development of SBSP as a viable energy solution, encouraging further technological and conceptual innovations. This resurgence reflects a growing recognition of the role that space-based energy generation could play in meeting the world’s future energy needs.

This renewed focus has been accompanied by various initiatives and programs around the world aimed at exploring the technological, economic, and environmental feasibility of SBSP systems [18]. In particular, the Space Solar Power Incremental Demonstrations and Research Project (SSPIDR) is a US initiative carried out by the Air Force Research Laboratory toward the development of scaled prototypes of critical SBSP systems and components, rather than a fully developed system concept. [19]. The Japan Aerospace Exploration Agency (JAXA) is advancing the OHISAMA project [20], which aims to develop a commercially viable SBSP system. JAXA has already conducted relevant experiments in wireless power transmission and plans to launch demonstration satellites in the near future. Similarly, the China National Space Administration (CNSA) plans to deploy a pilot SBSP system in 2030 and a fully operational system by 2050 [6]. In addition, the activity on SBSP conducted by the Korea Aerospace Research Institute (KARI) has achieved a major breakthrough in 2023 [21] by demonstrating energy transfer over a distance of 1.8 km, together with the identification of areas of improvement, such as transmission efficiency and beam pointing precision. The Canadian Space Agency (CSA) fosters innovation in SBSP through its annual Space Solar Power Competition [22], which encourages students to design and propose SBSP concepts. Finally, the ESA SOLARIS program aims to develop initial concepts for future SBSP systems [23]. The program focuses on addressing key technical challenges, such as the efficient transmission of energy from space to Earth and the construction of large-scale solar arrays in orbit.

In addition to the efforts of major space agencies worldwide, the Caltech Space Solar Power Project (SSPP) has focused on several key research areas in recent years. These include implementing power-optimal guidance strategies for planar SBSP satellites [24], developing ultralight photovoltaic materials that are both efficient and resistant to radiation [25], designing deployable lightweight structures to support large-area arrays [26], and advancing wireless power transmission through scalable phased array antennas [27]. In 2023, SSPP achieved a significant milestone with the launch of the Space Solar Power Demonstrator (SSPD-1) [28,29]. This 10-month mission successfully tested the three critical technologies providing valuable insights into the performance and durability of these technologies in the space environment, informing future designs and advancing the feasibility of space-based solar power systems.

Finally, it is noteworthy that the International Academy of Astronautics has recently established a Permanent Committee for Space-Based Solar Power [30].

2.3. SBSP concepts

Table 1 provides an overview of several SBSP concepts proposed by different international organizations, each with its distinct strengths and design characteristics.

Specifically, the “SPS-ALPHA Mark 4” is rated to deliver a power output of 1 GW, utilizing concentrated photovoltaics (C-PV) technology in a large circular configuration with a diameter of 6 kilometers. This design emphasizes maximizing energy production while maintaining a moderate mass of 3200 tons.

The “CASSIOPEIA” concept, developed through collaboration between the UK Space Agency and ESA, focuses on efficiency. It also uses C-PV technology to deliver 1.4 GW of power. In addition to its compact and lightweight design at 2064 tons and measuring 5 by 2

Table 1
Major SBSP concepts with main designs parameters.

Concept	SPS-Alpha MK-VI (USA)	CASSIOPeiA (UKSA-ESA)	TASI Concept (ESA)	MR-SPS (CNSA)	K-SSPS (KARI)
Rated Power to Grid (GW)	1	1.4	1	1	2
Orbit	GEO	GEO	GEO	GEO	GEO
Major Spread Dimension (km)	6	5	4.13	10	6.8
Mass (tons)	3200	2064	6600	9160	10 000
Generation Type	C-PV	C-PV	PV	PV	PV
Micro-Wave Radiation Frequency (GHz)	5.8	5.8	5.8	5.8	5.8
Ground Rectenna Radius (km)	1.8	3.2	7.5	–	4

kilometers, CASSIOPeiA incorporates an innovative power transmission method using rotary phased arrays [31].

It is also worth mentioning the design proposed by Thales Alenia Space to ESA in a pre-phase-A study, characterized by a relatively high mass of 6600 tons and large dimensions, measuring 2.5 by 4.13 kilometers. It offers 1 GW of power to the grid. Its main components are relatively simple, focusing on regular PV arrays to collect solar energy and a circular phased array antenna for wireless power transmission.

Similarly, China's "MR-SPS" concept is characterized by large linear dimensions, measuring 12 by 1 kilometer, also producing 1 GW of power to the grid. Its design is very similar to the one proposed by Thales Alenia Space consisting of PV arrays and a phased array antenna. However, despite its extremely large dimensions, its mass is reported to be just 1800 tons, which suggests a mass optimization for a more efficient deployment and scalability.

Finally, the "K-SSPS" concept, capable of providing 2 GW of power, was developed by the Korea Aerospace Research Institute (KARI). Its dimensions measure 6.8 by 2.2 kilometers, while its total mass reaches 10000 tons. This design reflects a focus on achieving the maximum power output.

3. Orbital capacity estimation scenarios

This section presents, to the authors' best knowledge, the first model to estimate the number of SBSP stations which can be positioned in GEO orbit. The model progresses from an idealized theoretical scenario to increasingly more realistic ones by adding more constraints. It examines the effects resulting from satellite spacing, existing GEO satellites, geographic restrictions, and population density, with the aim of optimizing the placement of the SBSP constellation and maximizing its power output.

One of the most important parameters that need to be introduced is the Intrinsic Orbital Capacity (IOC) which defines the maximum number of satellites that can physically populate a specific orbit without causing interference or collision. IOC is crucial for understanding the limitations of placing multiple satellites in GEO orbit, which is a prime location for SBSP constellations. In the context of GEO orbit, each satellite requires a certain amount of orbital "real estate" to maintain its position and function without interfering with adjacent satellites. This spacing is determined by the size of the satellite, the precision of its orbital station-keeping capabilities, and the need to avoid radio frequency interference [32]. To account for these factors, we introduce the Minimum Distance Angle (MDA), which defines the physical angular separation between two adjacent satellites and will be treated parametrically for each scenario, allowing assessment of how different angular separations impact the achievable IOC.

IOC directly influences the maximum power output that can be achieved by an SBSP constellation. Indeed, since each satellite forming an SBSP constellation is responsible for collecting solar energy and

transmitting it to Earth, the total power output of the constellation is a monotonically increasing function of the number of satellites that can be deployed in orbit. Ultimately, the estimation of GEO IOC may prove to be of paramount importance in determining the feasibility and scalability of SBSP constellations. In developing an estimation model for IOC, several assumptions were made. These assumptions vary across four different scenarios were considered, as illustrated below, each progressively incorporating more complex and realistic conditions.

3.1. Scenario 1

Assumptions:

- 1.1 Geosynchronous Earth Orbit (GEO):** All SBSP stations are placed in a Geosynchronous Earth orbit, maintaining a fixed position relative to Earth's equator.
- 1.2 Minimum Distance Angle (MDA):** A minimum angular distance between two subsequent SBSP stations, as shown in Fig. 1, is imposed.
- 1.3 Zero inclination, zero eccentricity:** Only the longitude of each SBPS satellite is considered. The eccentricity and inclination of the satellites are assumed to be exactly zero. Notably, if a satellite has a non-zero inclination, it is assumed to *de facto* occupy its GEO longitude, as it periodically crosses the equatorial position at the Right Ascension of the Ascending Node (RAAN) and again after half of its orbit.
- 1.4 Single Earth receiving antenna:** A single, global receiving antenna on the entire Earth surface is assumed, capable of collecting power from all power-transmitting SBSP stations simultaneously.
- 1.5 Empty GEO orbit:** GEO orbit is assumed to be completely empty, with no existing orbital objects.

Implementation:

In this scenario, the absence of orbital congestion or interference creates an idealized condition in which GEO orbit is entirely available for SBSP stations. Therefore, the number of SBSP stations that can be placed in GEO orbit is maximized, making this scenario a theoretical upper bound for IOC.

3.2. Scenario 2

Assumptions: All assumptions of Scenario 1 except 1.5 are considered for Scenario 2. Assumption 1.5 is substituted with:

- 2.1 Existing GEO Satellite Population Considered:** The current population (year 2025) of GEO satellites is considered, hence reducing the orbital slots for SBSP stations from Scenario 1.

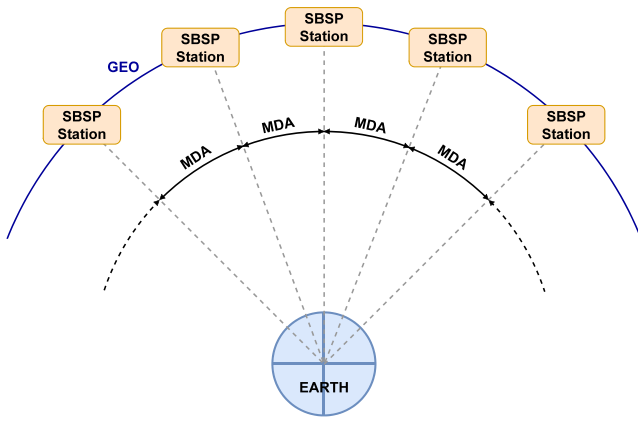


Fig. 1. Representative schematics of Scenario 1. SBSP stations are inserted in a free-of-satellites GEO.

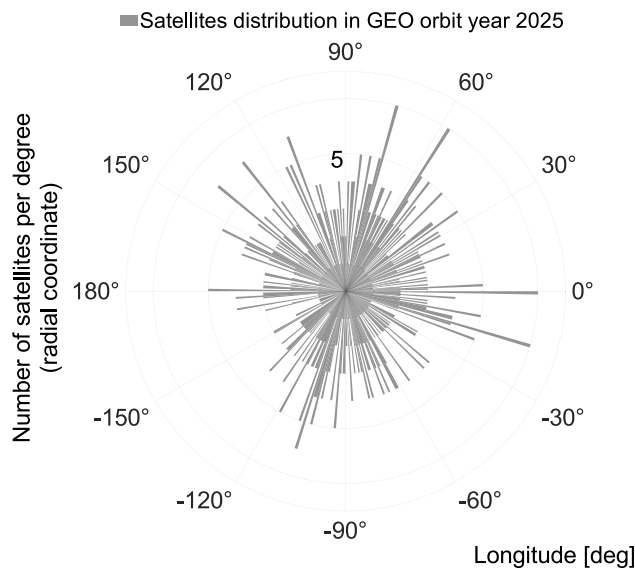


Fig. 2. Satellite distribution in GEO orbit (year 2025) plotted vs longitude. Longer bars describe a higher number of satellites.

Implementation: The current population of GEO satellites is drawn from available public databases [33] resulting in 1 degree precision density plot reported in Fig. 2.

The available free arcs between the longitudes of existing satellites are then identified. The MDA is applied to determine how many SBSP stations can be safely placed within each arc. The procedure for applying the MDA constraint follows few steps. First, the angular difference $\Delta\beta$ between the longitudes of each pair of existing satellites is computed. The maximum number $N_{station}$ of SBSP satellites that can be placed within each arc is determined by dividing $\Delta\beta$ by MDA and rounding down the result to ensure that the stations are spaced safely.

$$N_{station} = \frac{\Delta\beta}{MDA} \quad (1)$$

After determining the maximum number of SBSP stations that can fit within each arc, the stations are evenly spaced by dividing the angular difference by the number of stations. The schematics of the criteria are reported in Fig. 3.

This scenario provides a more accurate estimate of IOC of GEO for SBSP stations than Scenario 1, under realistic conditions, taking into account both the existing satellite population and necessary operational constraints.

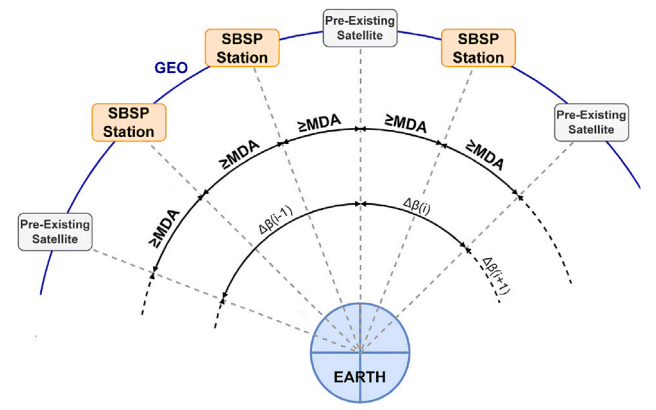


Fig. 3. Representative schematics of Scenario 2. SBSP stations are inserted in GEO orbit already occupied by pre-existing satellites.

3.3. Scenario 3

Assumptions: In addition to the assumptions 1.1, 1.2, and 1.3 of Scenario 1, together with assumption 2.1 of Scenario 2, the following additional assumptions are adopted:

3.1 Longitude Geographical Constraints on Earth: Only regions on Earth within ± 0.05 deg of longitude around the SBSP station and within ± 30 deg of latitude are considered to receive power from the SBSP stations.

3.2 Land Constraint: Given the previous assumption, only regions completely covered by land are considered suitable for accommodating receiving antennas.

Implementation:

The longitude range of ± 0.05 deg identifies a large enough area capable of accommodating the receiving antenna. This corresponds to an arc length s on the Earth's surface defined by the equation

$$s = 0.1 \frac{\pi}{180} R_E \quad (2)$$

Where R_E is the radius of Earth at the equator. The arc s is approximately 11 km long and ensures that receiving antennas, which in most designs reach up to 7 km in diameter as reported in Table 1, can be placed at the designated longitudes while being able to intercept the full electromagnetic radiation from the SBSP stations. In addition, by employing the ESA World Cover dataset [8], each selected longitude is checked to ensure that the corresponding surface coverage is associated with a land area large enough to accommodate the receiving antenna, so water areas are not considered suitable for this purpose. If the data show a full land coverage within ± 0.05 deg range, the longitude is considered valid for placing a receiving antenna. Furthermore, the assumption of a latitude range between -30 and 30 degrees was taken on the basis of the footprint evaluation associated to satellites in GEO orbit, namely the satellites beaming footprint. At higher latitudes, the SBSP satellites footprint expands, affecting the feasibility of placing sufficiently large receiving antennas. To ensure that an antenna capable of receiving the full transmitted power can be accommodated, the footprint was calculated at various latitudes by using the satellite transmission wavelength λ and the diameter ϕ_{ant} of the satellite emitting antenna as input parameters.

Specifically, these quantities determine the beamwidth angle θ which represents the aperture of the main lobe of the power transmission beam. Taking into account common beam-shapes and accounting for a total beam reception [34], θ can be calculated as

$$\theta = 2 \left(70 \frac{\lambda}{\phi_{ant}} \right) \quad (3)$$

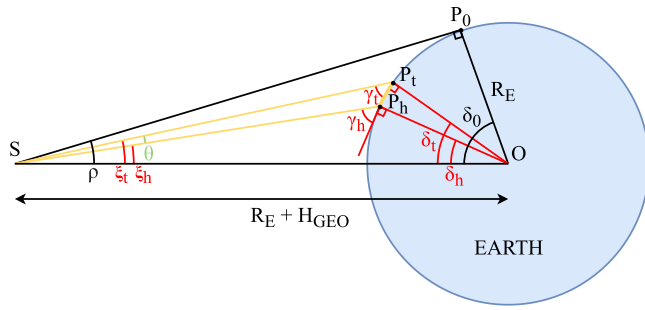


Fig. 4. Schematization of the footprint for SBSP stations placed in GEO orbit.

Thus, assuming a transmitting frequency f of 5.8 GHz (see Table 1), and an emitting antenna characterized by a diameter of 1 km, the beamwidth angle can be calculated

$$\theta = 2 \left(70 \frac{c}{f \phi_{ant}} \right) = 0.00724 \text{ rad} \quad (4)$$

Once θ is determined, the footprint is given by the intersection of the corresponding beam cone with the Earth's surface (in Fig. 4 defined by the yellow line joining the points P_h and P_t , representing the heel and the toe of the footprint, respectively). In this regard, it is of crucial importance to determine the maximum angle ρ defining the maximum inclination at which the SBSP satellites can point on Earth. By looking at Fig. 4, ρ is defined by the line between the SBSP satellite located at point S and the center of Earth O, and the tangent from the satellite S to the Earth's surface (Earth is assumed as a perfect sphere) at the point P_0 . Considering that both the radius of Earth R_E and the GEO orbit H_{GEO} are known quantities, the angle ρ can be promptly calculated by

$$\sin(\rho) = \left(\frac{R_E}{R_E + H_{GEO}} \right) \quad (5)$$

Hence, by defining $\xi_t = \xi_h + \theta$ (see Fig. 4), it is immediately understood the importance of the angle ρ as it represents the upper limit of ξ_t . If $\xi_t > \rho$, at least part of the radiation emitted by the SBSP satellite would not reach Earth.

However, the footprint representation provided in Fig. 4 (line P_h - P_t) is only part of the story. Indeed, given the small value of θ , the curved surface of Earth can be approximated with a flat 2-dimensional surface, resulting in an elliptical footprint [35] of length FP_l (i.e., along longitude, the segment P_h - P_t) and width FP_w (i.e., along latitude, out of plane in Fig. 4). These two quantities can be estimated by observing that

$$\cos(\gamma) = \frac{\sin(\xi)}{\sin(\rho)} \quad (6)$$

With the angle δ given by

$$\delta = \frac{\pi}{2} - \xi - \gamma \quad (7)$$

Thus, the length of the ellipse associated with the footprint is found as

$$FP_l = (\delta_t - \delta_h) R_E \quad (8)$$

with δ_t and δ_h expressed in radians.

Finally, since the SBSP stations are uniquely associated with a specific longitude while pointing at different latitudes, the width of the footprint depends only on the distance $\overline{SP_t}$ between the SBSP transmitter S and its target point P_t [35]:

$$FP_w = R_E \operatorname{asin} \left(\frac{\overline{SP_t} \sin \theta}{R_E} \right) \quad (9)$$

This result allows for the evaluation of the footprint, which is given by

$$FP = \frac{\pi}{4} FP_l \cdot FP_w \quad (10)$$

To better visualize the effect of the aiming latitude on the footprint dimensions, in Fig. 5(a) are reported the satellites' transmission cones pointing at 0 deg, 15 deg, and 30 deg of latitude, with the actual footprints displayed in Fig. 5(b).

In detail, the footprint was evaluated for latitudes from 0 to 60 degrees and reported in Fig. 6. The results show that by increasing the latitude, a second-order increase of the footprint occurs. In this respect, the latitude range between -30 deg and +30 deg, with a corresponding area varying from approximately 16 km² (0 deg latitude) to 21 km² (± 30 deg latitude), is chosen as a suitable range for the accommodation of manageable receiving antennas.

3.4. Scenario 4

Assumptions: In addition to the assumptions 1.1, 1.2, 1.3, 2.1, 3.1, and 3.2, the following additional assumption is adopted:

4.1 Population Density Constraint: Only areas where the population density exceeds 3000 people per square kilometer are considered suitable for placing receiving antennas.

4.2 Correspondence 1-to-1 between SBSP station and receiving antenna: A specific SBSP station can target only one specific receiving antenna on Earth.

Implementation:

In this scenario, population density is used as a criterion to identify regions where the necessary infrastructure for energy distribution is more likely to be present. Indeed, it is understood that a minimum threshold of population density should be identified to guarantee the presence of the aforementioned infrastructures. The Gridded Population data of the World map from the Socioeconomic Data and Applications Center (SEDAC) [36] is used to identify areas with a population density exceeding the chosen threshold. A reasonable threshold is determined by evaluating, with 3000 people per km² representing a medium-high density populated area, where it is very probable to find the necessary infrastructure.

For this scenario, since a dataset with a 0.1 deg longitude resolution is needed (see assumption 3.1), it necessitates down-scaling and interpolation of the original 30 s resolution dataset from SEDAC to match this precision. After interpolation, each longitude is examined and, where multiple regions exceed the population density threshold, only the location with the highest population density is selected for placing a receiving antenna (see assumption 4.2). The result of this calculation identifies the suitable locations for accommodating a receiving antenna under the assumptions of Scenario 4, as shown in Fig. 7.

4. Intrinsic orbital capacity evaluation

In this section, we present the results of the orbital capacity analysis for each of the scenarios introduced in Section 3. IOC is calculated on the basis of the different constraints outlined in each scenario, providing an upper bound for the placement of SBSP stations.

4.1. Scenario 1

The intrinsic orbital capacity in GEO orbit can be directly calculated using a simple inverse linear equation

$$IOC = \frac{360}{MDA} \quad (11)$$

Here, MDA is in degrees. This relation can be better visualized in Fig. 8 and this result provides a theoretical upper bound on the number of stations, assuming that there are no other constraints. It is to be noticed that a minimum MDA value of 0.1 has been set due to the limitation associated with the dataset resolution.

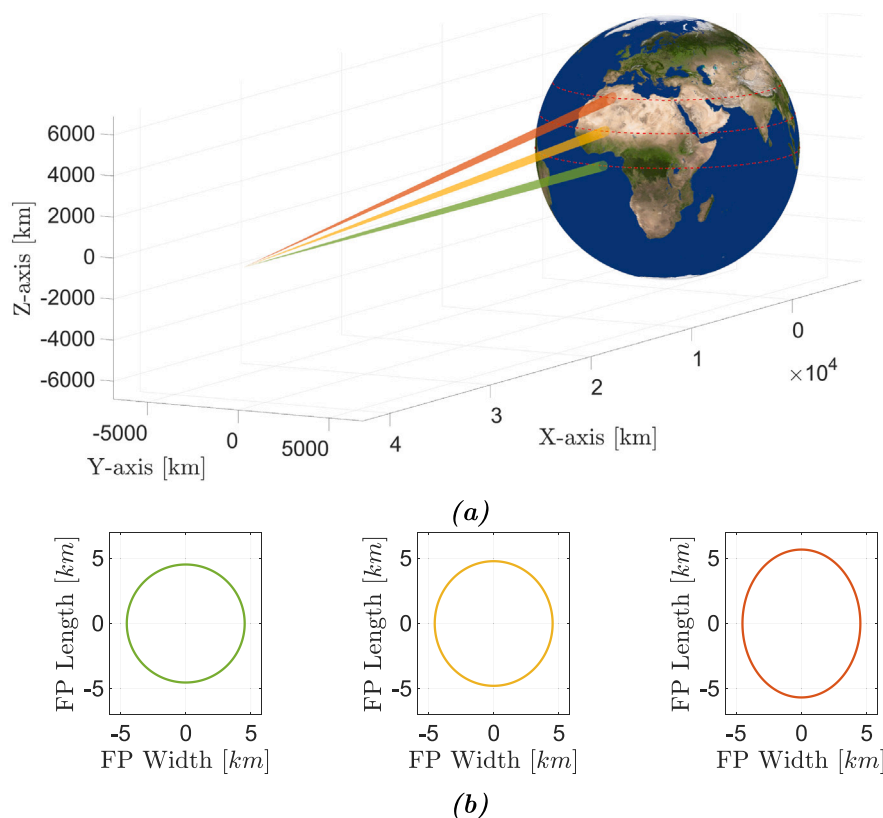


Fig. 5. (a) Beam cone representation at 0 deg, 15 deg and 30 deg pointing latitude. The aperture angles are scaled by a factor of 100 for easier visualization. (b) From left to right, footprint (FP) at 0 deg, 15 deg, and 30 deg pointing latitude.

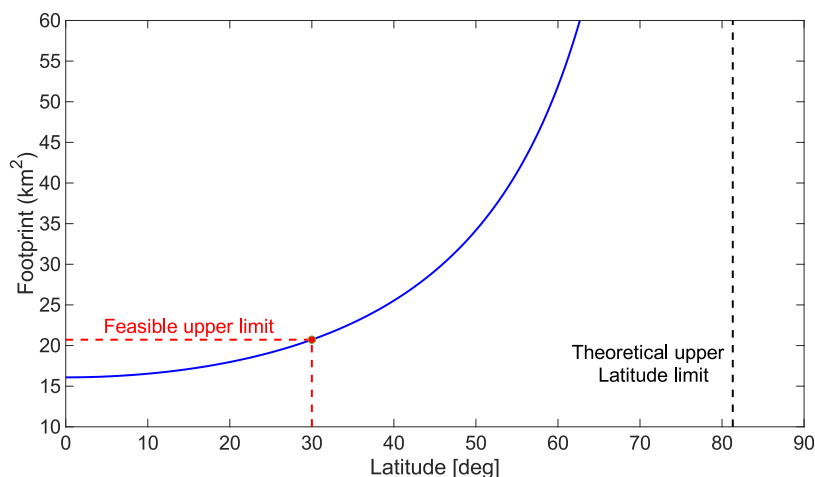


Fig. 6. Footprint associated with SBSP satellites pointing at different latitudes. The red dashed line highlights the upper chosen latitude for accommodating receiving antennas. The black dashed line describes the tangent point P_0 as in Fig. 4.

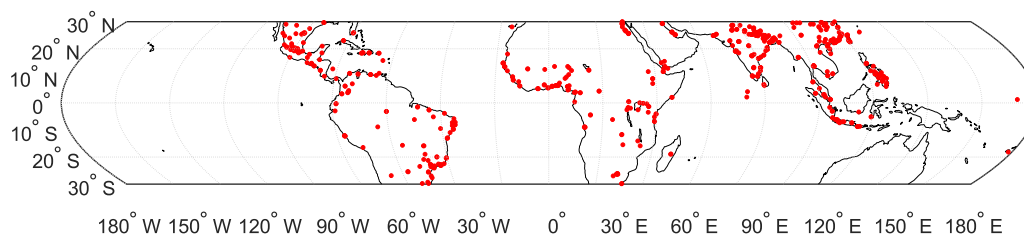


Fig. 7. Locations with a population density over the threshold of 3000 inhabitants/km².

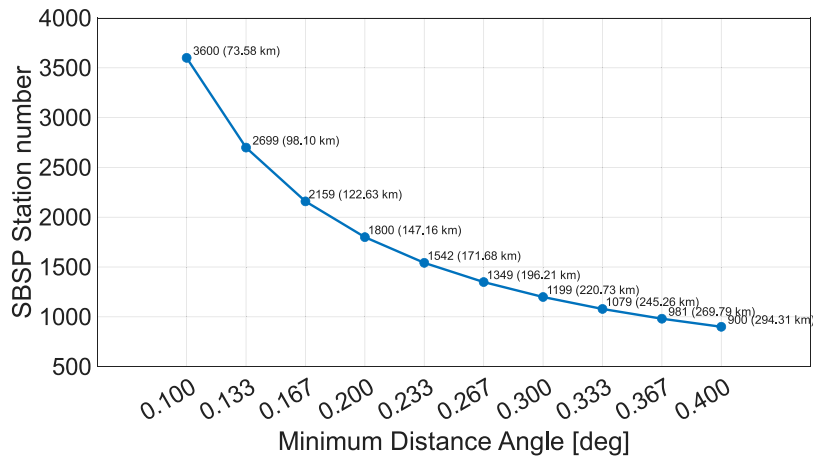


Fig. 8. Scenario 1 — Maximum GEO orbital capacity for SBSP stations and corresponding distance arc in km by varying MDA.

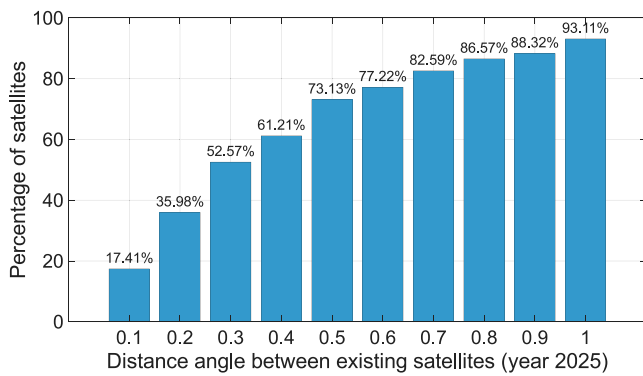


Fig. 9. Percentage of current (year 2025) GEO satellites at different separation angles.

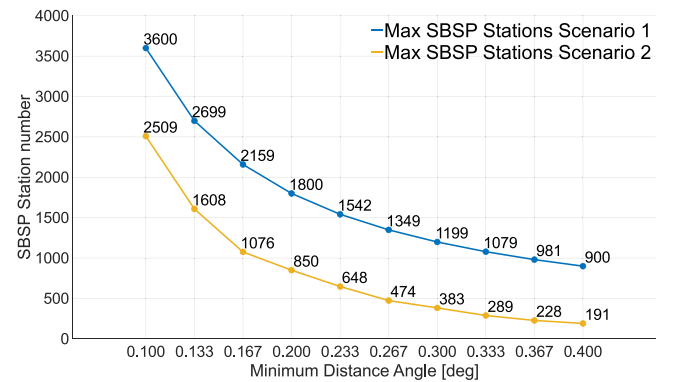


Fig. 10. IOC for SBSP stations by varying MDA when considering pre-existing GEO satellites (year 2025 satellites distribution).

4.2. Scenario 2

In this scenario, to determine the available space for the deployment of SBSP stations, a parametric evaluation based on multiple MDAs is conducted. Furthermore, also in this scenario, the analysis considers a minimum MDA equal to 0.1 degrees, which corresponds to a distance arc of approximately 73 km in GEO orbit. The calculation for this arc is based on the relationship between MDA and the circumference of the orbit, given by the equation

$$d = \frac{MDA}{360} \times 2\pi R \quad (12)$$

Where $R = R_E + H_{GEO}$, with R_E the radius of Earth at the equator and H_{GEO} the altitude of GEO orbit from the Earth's surface.

Given the graphical explanation of MDA provided in Fig. 3, it is understood that an MDA of 0.1 degrees provides about 147 km of aperture range around each station, ensuring safe conditions for satellite operation.

However, in this scenario, there is the need to take into account the distribution of the existing satellites in GEO orbit (year 2025). In this regard, only about 17% of them is spaced 0.1 degrees apart, as shown in Fig. 9, therefore larger MDA also need to be considered for a more complete evaluation.

The results are shown in Fig. 10, and reveal a monotone reduction of IOC upon increase of MDA. Furthermore, a comparison with Scenario 1 is provided, showing that Scenario 2 can accommodate a lower number of SBSP satellites than Scenario 1, due to more stringent assumptions.

Considering the need to maximize the presence of SBSP satellites in GEO orbit, MDA equal to 0.1 is taken as the value of reference. At

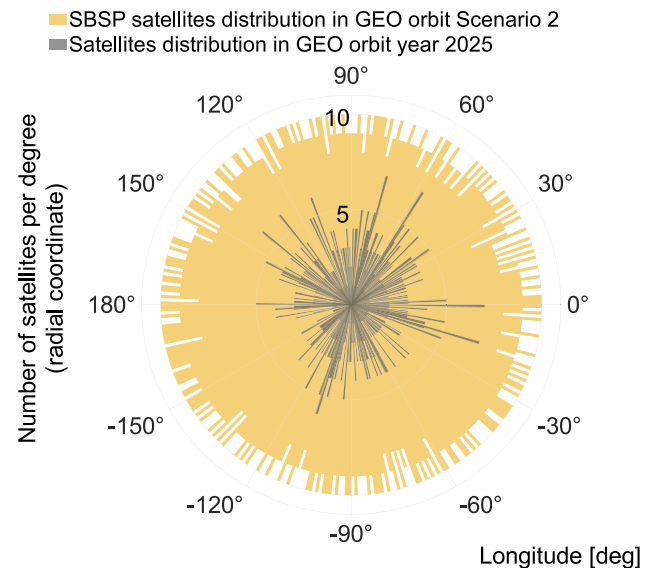


Fig. 11. Satellites in GEO orbit: comparison between the current satellites distribution (year 2025) and Scenario 2. MDA is equal to 0.1 deg.

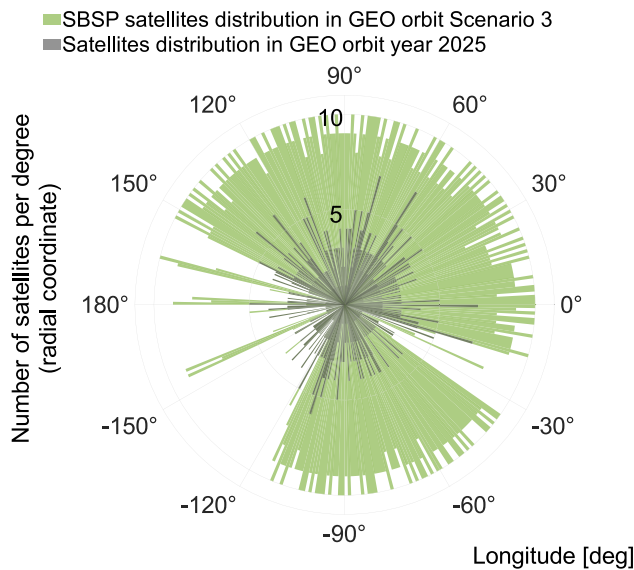


Fig. 12. Satellites in GEO orbit: comparison between the current satellites distribution (year 2025) and Scenario 3. MDA is equal to 0.1 deg.

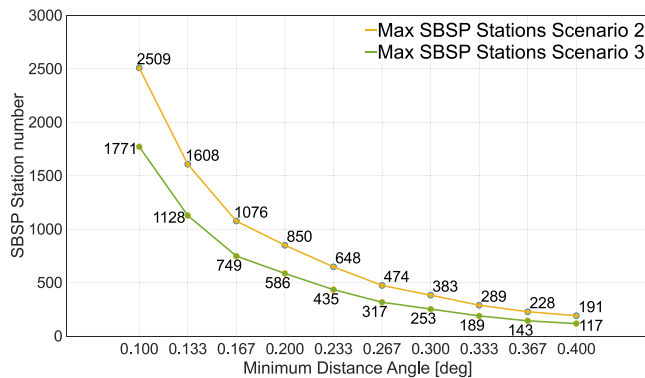


Fig. 13. Maximum GEO orbital capacity for SBSP stations by varying MDA when considering Scenario 3 constraints (green line). Comparison with Scenario 2 (yellow line) is also provided.

this MDA value, the SBSP satellite population shows a nearly uniform distribution over the longitude, as shown in Fig. 11, with almost every longitude supporting approximately 10 satellites per degree.

4.3. Scenario 3

The dataset used to identify suitable longitudes, namely areas completely covered by land (see assumption 3.2), is the ESA Land Cover Dataset [8]. This dataset provides data with a resolution of 10 m, which results to be very useful for identifying regions where land is *continuous enough* to host large-scale receiving antennas. This scenario eliminates vast portions of the orbit above oceans and other unsuitable locations. Following the implementation of the constraints explained in Section 3 the results indicate a reduction of the maximum number of deployable SBSP stations compared to the previous scenarios.

This decrease is largely attributed to the additional geographic constraint that limits station placement to longitudes over land between -30 deg and 30 deg latitude and can be more clearly visualized in Fig. 12 which shows that once the constraints of Scenario 3 are applied, there is a clear reduction with large gaps in the satellite density over longitudes corresponding to oceanic regions.

This result is confirmed by Fig. 13, where Scenario 2 and 3 are compared at different MDAs. While they both show a decaying behavior

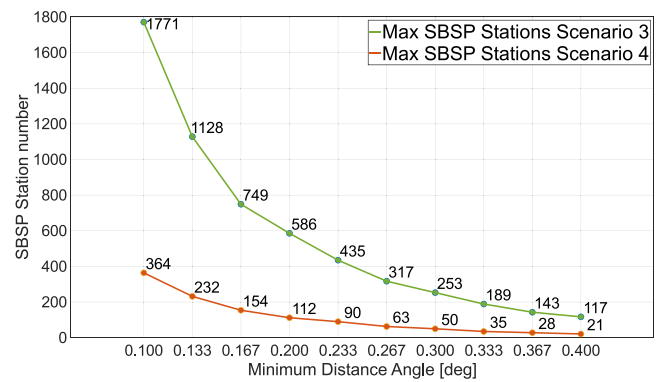


Fig. 14. Maximum GEO orbital capacity for SBSP stations by varying MDA when considering Scenario 4 constraints (orange line). Comparison with Scenario 3 (green line) is also provided.

upon MDA increase, similarly to Scenario 1, it occurs that Scenario 3 can deploy a lower number of satellites than Scenario 2, even though no dramatic reductions are observed.

4.4. Scenario 4

For this particular scenario, the constraints prove to be the most stringent, with only 364 orbital slots meeting the model assumptions, accounting for an MDA of 0.1 deg. These results are illustrated in Fig. 14 and can be directly compared to the previous scenarios. In particular, the constraint on the placement of the receiving antenna based on high population density determines another reduction of the maximum orbital capacity. Indeed, the most densely populated areas are often concentrated within a very narrow range of longitudes compared to the broader distribution of generic land. With this constraint, the maximum theoretical population capacity from Scenario 1, which represents a purely theoretical upper bound, is reduced by approximately 89.9% for an MDA of 0.1 deg.

Finally, Fig. 15 shows the comparison of the number of satellites per degree between Scenario 4 and the present (year 2025) satellites distribution. As easily understood, the satellites concentrate mainly on the most populated regions, creating clusters saturating the few remaining viable slots.

The outcome of Scenario 4 suggests that the population constraint might be more critical compared to the other constraints applied to the previous scenarios and must be given serious consideration in future evaluations of SBSP systems.

5. Maximum power output

This section outlines the methodology employed to model and assess the power output of a Space-Based Solar Power constellation. The analysis relies on several key assumptions, with the model estimating the generated power based on the amount of incident solar radiation and the orientation of each SBSP station relative to the Sun. The power output is then integrated over time to yield annual energy production estimates in various scenarios.

5.1. Model assumptions

To generate a model to evaluate the SBSP output, the following key assumptions are made:

1. The SBSP station considered in this model is located in GEO orbit.
2. The Sun's rays are assumed to be parallel to the line connecting the center of the Sun and the center of Earth.

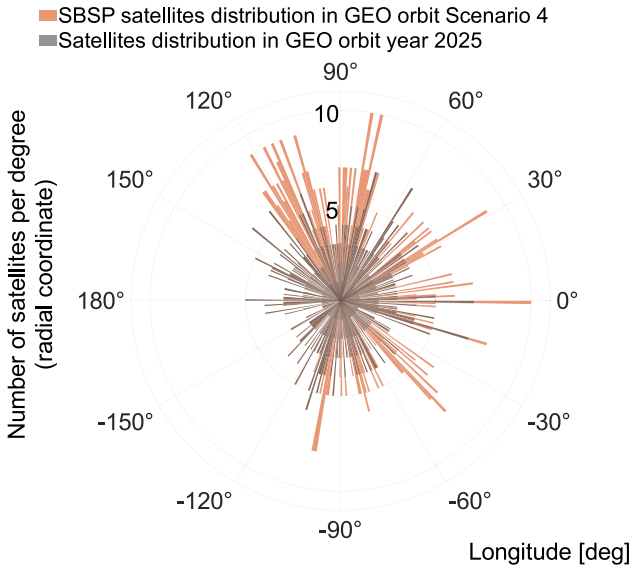


Fig. 15. Satellites in GEO orbit: comparison between the current satellites distribution (year 2025) and Scenario 4. MDA is equal to 0.1 deg.

3. The SBSP station is modeled as a flat surface always perpendicular to the line connecting its center of mass (COM) and the target point on Earth's surface (i.e., the ground receiver).
4. Energy generation occurs only on the side of the SBSP station covered by solar panels.
5. Energy storage systems are not considered on board the SBSP station. Power can only be produced and transmitted when the panels are illuminated by sunlight, limiting the transmission window to periods of direct sunlight exposure.

5.2. Model implementation

The power generated by the SBSP stations depends on the incident solar power and the orientation of the solar panels relative to the sunlight. The equation quantifying the generated solar power can be expressed as

$$P = A\eta S \cos(\nu)K \quad (13)$$

Where A is the area of the solar panels, η is the conversion efficiency of the solar cells, S is the solar irradiance, ν is the angle between the sunlight direction and the normal to the surface of the solar panels, and K is defined as the incidence angle modifier. The latter is the ratio of the product of transmittance and absorbance at a specific incidence angle to the product of transmittance and absorbance at normal incidence. It is used to estimate the performance of a solar collector for sunlight impinging along directions that strongly deviate from the normal to the surface of the solar collectors. It is defined as [37]

$$K = 1 - b_0 \left(\frac{1}{\cos(\nu)} - 1 \right) \quad (14)$$

where b_0 takes into account both the refraction and the reflection due to the solar cells' cover, taking a value of 0.136 for single-cover collectors [37].

To calculate the energy output over an entire year, since A , η and S can be considered fixed design parameters, it is necessary to determine the time evolution of the angle of incidence ν . This can be estimated by relating ν to the following three primary angles:

- Hour angle (ψ): reflects the position of the SBSP station relative to the Sun. As the SBSP station remains geostationary, the hour angle dictates the degree of exposition of the SBSP station to

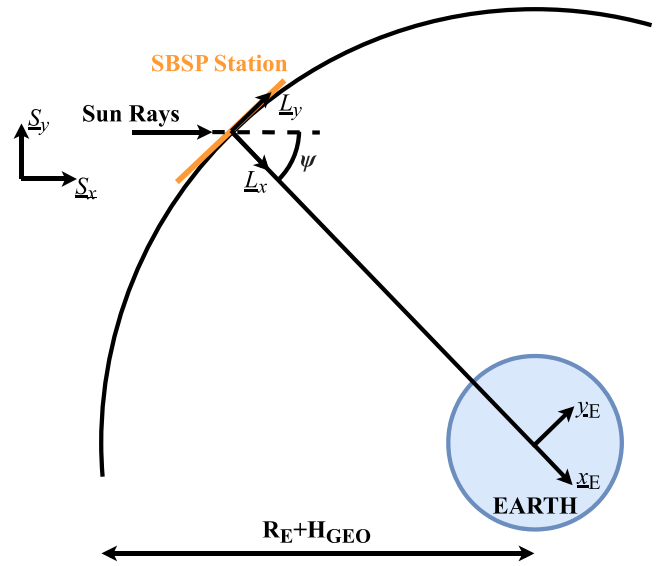


Fig. 16. Incidence of the Sun's rays with respect to the hour angle ψ . S_x and S_y describe the reference system of the Sun, while L_x and L_y describe the reference system of the SBSP station. ψ lies in the equatorial plane $x_E - y_E$, with x_E and y_E the reference system of Earth.

sunlight, hence accounting for Earth's rotation. As illustrated in Fig. 16, $\psi = 0$ means maximum exposure of the SBSP to the Sun.

- Solar Declination angle (ϵ): is the angle between the Earth's equatorial plane and the direction of the Sun's rays as illustrated in Fig. 17. It accounts for the tilt of the Earth's axis and varies throughout the year. The solar declination angle can be calculated in degrees using the equation derived by [38]

$$\epsilon = 23.45 \sin \frac{360}{365} (284 + i) \quad (15)$$

Where i is the day of the year with January 1st being $i=1$.

- Aiming angle (α): is the angle between the normal to the SBSP station, also pointing towards its target on Earth's surface, and the Sun's rays, as illustrated in Fig. 18.

It is noteworthy that ϵ and α lie in the same plane, so they can be simply summed to obtain a single rotation angle ϵ_{tot} .

To calculate the overall incidence angle ν , we start by considering three distinct reference frames, referring to Earth, Sun and the SBSP station. The Earth's reference system is defined by the normal axis x_E , y_E , and z_E . Here, x_E and y_E identify the equatorial plane. Similarly, the rotating reference frame fixed on the Sun, is defined by the normal axis S_x , S_y , and S_z . In particular, S_x is aligned along the line connecting the center of the Sun and the center of the Earth, S_z belongs to the plane normal to the Earth equatorial plane, while S_y forms an orthonormal triad with the other two axes. Finally, the reference frame with its origin at the center of mass (COM) of the SBSP station, is defined by the three normal axis L_x , L_y , and L_z . Specifically, L_x is normal to the SBSP station and extends from the SBSP station towards the aiming point on Earth. L_y and L_z are aligned along the two edges of the SBSP station.

Given these frames definitions, the angle of incidence ν results as the angle between S_x and L_x . In the Sun's reference frame, S_x can be represented by the unit vector

$$\hat{S}_x = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} \quad (16)$$

The corresponding x -axis unit vector in the SBSP reference frame ($\hat{L}_x$) can be obtained at any given moment by applying two consecutive

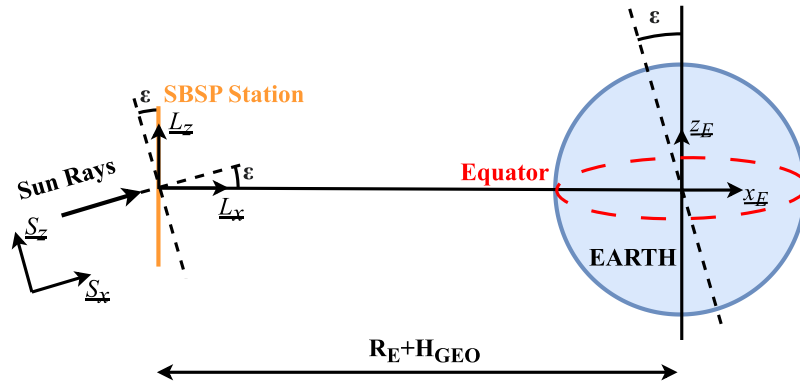


Fig. 17. Incidence of the Sun rays with respect to the solar declination angle ϵ . S_x and S_z describe the reference system of the Sun, while L_x and L_z describe the reference system of the SBSP station. ϵ lies in the plane $x_E - z_E$, with x_E and z_E the reference system of Earth.

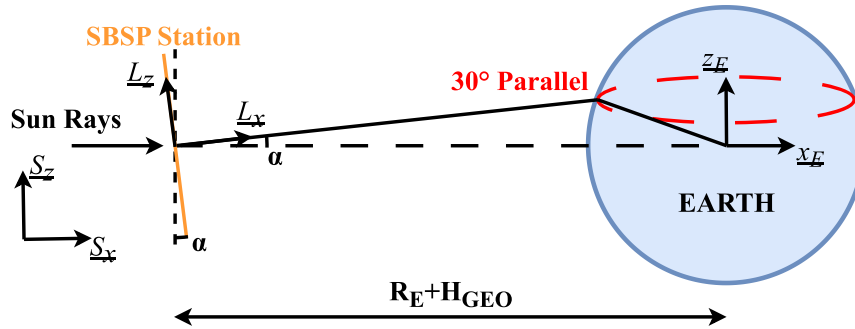


Fig. 18. Incidence of the Sun's rays with respect to the aiming angle α . S_x and S_z describe the reference system of the Sun, while L_x and L_z describe the reference system of the SBSP station. α lies in the plane $x_E - z_E$, with x_E and z_E the reference system of Earth.

rotations to the Sun's reference frame. The first rotation is around S_y by an angle that results from the algebraic sum of the Solar Declination angle ϵ and the Aiming angle α

$$\epsilon_{tot} = \epsilon + \alpha \quad (17)$$

This is followed by a second rotation around the z -axis (S_z) equal to the Hour angle ψ .

These rotations are described by rotation matrices that transform the unit vector from the Sun's reference frame to the SBSP reference frame. In particular, the first rotation matrix is

$$R_\epsilon = \begin{bmatrix} \cos(\epsilon_{tot}) & 0 & \sin(\epsilon_{tot}) \\ 0 & 1 & 0 \\ -\sin(\epsilon_{tot}) & 0 & \cos(\epsilon_{tot}) \end{bmatrix} \quad (18)$$

whereas the second rotation matrix is

$$R_\psi = \begin{bmatrix} -\cos(\psi) & \sin(\psi) & 0 \\ -\sin(\psi) & -\cos(\psi) & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (19)$$

By multiplying these matrices for the unit vector $\hat{S}_x$, it can be obtained

$$\hat{L}_x = R_\epsilon R_\psi \hat{S}_x = \begin{bmatrix} -\cos(\psi) \cos(\epsilon_{tot}) \\ -\sin(\psi) \cos(\epsilon_{tot}) \\ -\sin(\epsilon_{tot}) \end{bmatrix} \quad (20)$$

Finally, by applying the scalar product of $\hat{S}_x$ in the previous equation, and by recalling that

$$\cos(v) = \hat{S}_x \cdot \hat{L}_x \quad (21)$$

the final result is obtained.

$$\cos(v) = -\cos(\psi) \cos(\epsilon_{tot}) \quad (22)$$

By substituting this expression in Eq. (13), and by cycling through each hour of the day, the hourly power output for each station can be calculated. Importantly, this procedure is scalable, as by summing these hourly values provides the total daily energy output. Extending this process to each day of the year, we can calculate the total yearly energy output for each individual satellite. Then, by repeating this procedure for each considered SBSP station in the chosen scenario and summing the results for each station, the total yearly energy output for each scenario can be determined.

5.3. Energy output results

Based on the data reported in Table 1, a SBSP station area of 10 km² is assumed, with the efficiency of the solar panels set at 20%. Using these parameters and following the procedure illustrated in Section 5.2, it can be estimated the power generation profile for each day of the year and for each SBSP station. For example, in Fig. 19(a) is shown the power generation profile calculated specifically on March 21st (equinox) which shows a peak at 272.20 GW. Afterwards, to account for power losses during transmission and reception, an SBSP station capable of delivering 1 GW peak power to the grid is considered. The original profile is therefore scaled accordingly, resulting in the power generation profile shown in Fig. 19(b).

Under this drastic assumption (almost 300 times power output reduction), the yearly energy output of each scenario can be evaluated. Furthermore, in order to provide some context, the results are compared with the current global electricity consumption. In particular, the world total electricity consumption in 2024 was approximately 29038 TWh [39]. Therefore the total energy of the SBSP provided in one year to the grid is evaluated to be:

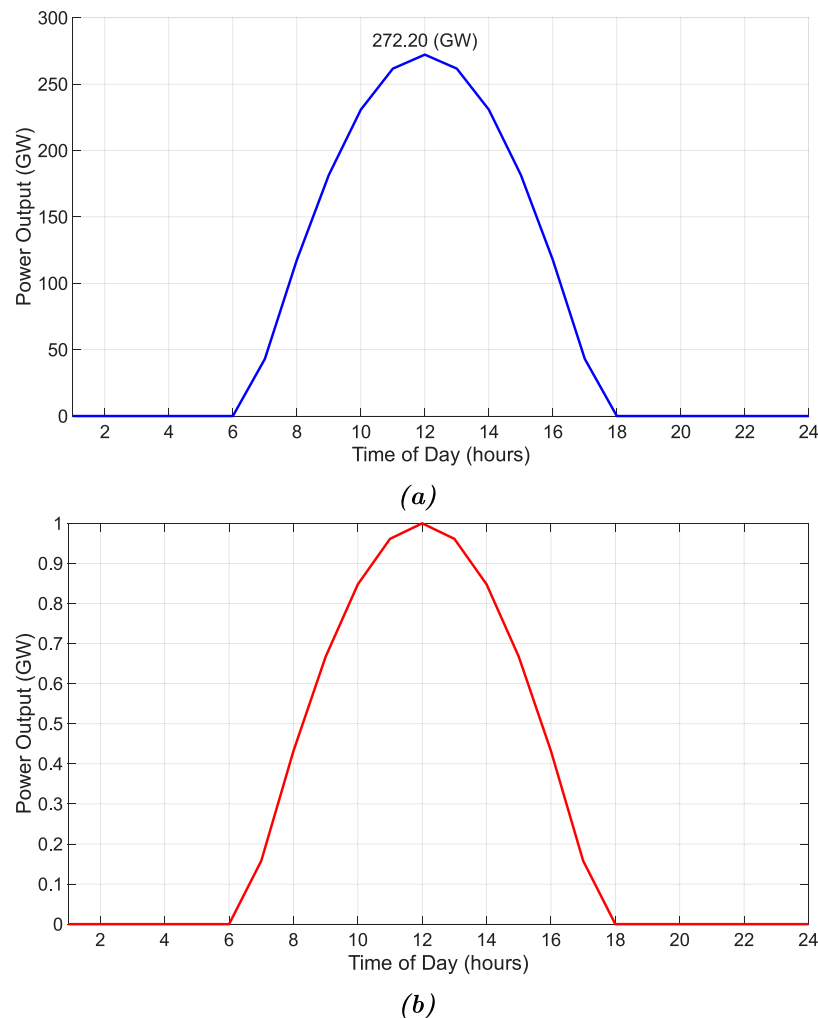


Fig. 19. (a) Power generation profile for March 21st. (b) Scaled power generation profile for March 21st.

- **Scenario 1:**

$$E_{S1} = 8902.60 \text{ (TWh)}$$

which represents 31% of the yearly global electricity consumption.

- **Scenario 2:**

$$E_{S2} = 6115.59 \text{ (TWh)}$$

which represents 21% of the yearly global electricity consumption.

- **Scenario 3:**

$$E_{S3} = 4315.29 \text{ (TWh)}$$

which represents 15% of the yearly global electricity consumption.

- **Scenario 4:**

$$E_{S4} = 900.15 \text{ (TWh)}$$

which represents 3% of the yearly global electricity consumption.

It is worth noting that the results presented for Scenario 4 do not solely depend on the choice of MDA but also on the minimum population density that was selected. This parameter plays a significant role in determining the suitable orbital slots that can be available, so the results can be recalculated and expressed as a function of both the MDA and the population density, as shown in Fig. 20. The

figure highlights that for small MDA and small population density, the energy output increases. Furthermore, for a better understanding of the model behavior, in the figure are also highlighted four energy output values, corresponding to four specific populations densities (i.e., 1000, 2000, 3000, and 4000). In this regard, the population density of 3000 inhabitants/km², chosen for the main results presented earlier in this section, remains a suitable choice providing a conservative estimate for the energy output of an SBSP constellation.

6. Conclusions

We have presented an analysis of the orbital capacity for Space-Based Solar Power stations in GEO orbit under a series of increasingly realistic constraints. The study has addressed four key scenarios, starting from an idealized case where the only limiting factor was the presence of a minimum distance angle between the SBSP stations and progressing to more stringent cases that incorporated geographical limitations, operational constraints, and population density considerations. The findings offer insights about the potential usefulness of a large-scale SBSP station deployment and identify the most critical factors that must be taken into account.

In terms of energy output, an evaluation model applicable to different scenarios has been proposed, reaching the conclusion that an SBSP constellation could provide energy to the grid, ranging from 31% to approximately 3% of the world's total energy consumption in 2024 depending on the considered scenario. Importantly, the evaluation criteria

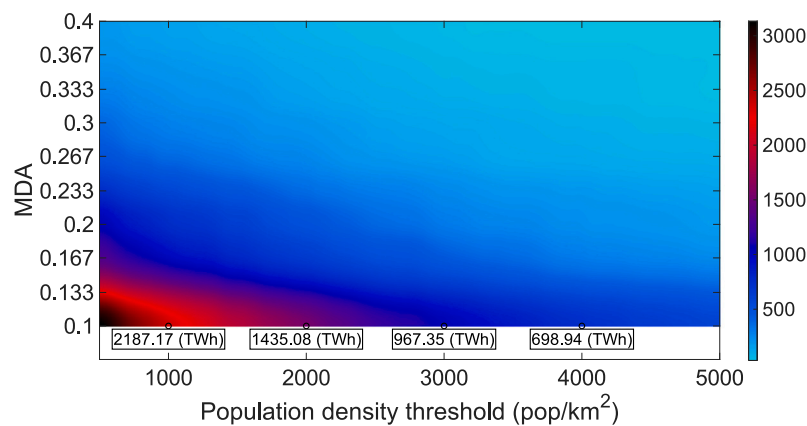


Fig. 20. Energy output by varying MDA and population density threshold. The results are in TWh.

used in this study, including geographical and population constraints, were selected by the authors as a reflection of current technological and infrastructural conditions. Depending on future advancements and policy changes, these constraints could be relaxed or modified, leading to more optimistic scenarios where a greater power output could be achieved. Although this was not the main focus of this paper, it is worth noting that more accurate and realistic results can be achieved by modeling and simulating the wireless power transmission and reception on the ground, which may be explored with more details in future works. Indeed, this would avoid imposing an arbitrary 300 times power output reduction, while instead adopting realistic values, possibly leading to better performance than the ones described in this work.

In addition, it should be highlighted that SBSP solutions are not limited to use on Earth only, and alternative applications such as providing energy to the Moon or Mars and to other satellites in Space are also viable.

In conclusion, this study not only shows the potential of SBSP stations to contribute to the global energy transition, but also highlights the substantial challenges associated with its implementation. Further research and development, particularly in optimizing station placement, managing orbital congestion, and developing reliable, cost-effective designs, is essential to unlock the full potential of SBSP technology.

CRedit authorship contribution statement

Armando Vittorio Atzori: Writing – original draft, Visualization, Resources, Methodology, Investigation, Data curation, Conceptualization. **Remo Proietti Zaccaria:** Writing – review & editing, Visualization, Validation, Supervision, Project administration. **Denis Garoli:** Writing – review & editing, Validation. **Marcello Romano:** Writing – review & editing, Validation, Supervision, Project administration, Conceptualization.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used AI-assisted tools solely to improve clarity and ensure correct grammar. These tools were limited to standard language correction utilities and did not involve the use of generative AI. No generative AI technologies were used in the creation, drafting, or content generation of this manuscript. The authors reviewed and manually edited all content to ensure accuracy and take full responsibility for the integrity of the publication.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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