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Annual Energy Output of a Space-Based Solar Panel for the North Region of Brazil

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Abstract

In the last decades, the use of orbital reflectors has been considered by several researches to collect solar power in outer space. The aim of this study is to estimate the annual energy output of a Space-Based Solar Panel (SBSP) in a Geosynchronous Earth Orbit (GEO), which is distributed to the capital cities in the North Region of Brazil: Belém, Boa Vista, Macapá, Manaus, Palmas, Porto Velho, and Rio Branco. In addition, the maximum energy output of the SBSP is compared to the annual energy demand of these cities. Because clean energy continues to dominate new power capacity, the proposed study aims to evaluate the energy transition towards a clean and uninterrupted energy, considering the total energy of a SBSP provided in one year to the North Region of Brazil and the current electricity consumption in this region. Since Belém, Boa Vista, Porto Velho, Macapá, Manaus, Palmas, and Rio Branco are located near the Earth's equator, the privileged geographical position of these cities permits that they experience roughly **12** hours of sunlight daily. Assuming a **12**-hour transmission window and neglected wireless transmission losses, the results showed that the total power output of a SBSP in a GEO could provide at least 13% to 100% of the electricity demand for the capital cities of the North Region of Brazil, establishing itself as a robust solution for energy security and sustainability for the Brazilian Amazon.

Keywords: Space-Based Solar Panel, North Region of Brazil, Renewable Energy, Geostationary Orbit, Energy Transition

1 Introduction

The transition towards clean energy in Brazil has been discussed by several institutions in the last decades [1]. Several researches have proposed Space-Based Solar Panel (SBSP) systems as an alternative to obtain solar power in outer space [2–6]. The advantage of a SBSP system with regard to Terrestrial solar panels is that space mirrors could collect uninterruptedly solar power due to they would not be at the mercy of weather conditions and day-night cycle. In particular, SBSPs represent an excellent alternative for countries like Brazil since its vast territorial and the high quantity of sunlight hours received per year, specially in the North Region of Brazil [7].

In this study, we assume a SBSP placed in a Geostationary Orbit (GEO), such that the solar panel (SP) maintains a fixed position relative to any observer on the Earth's surface, and the amount of solar energy collected by the SP would be transmitted wirelessly from the SBSP to a ground-based receiving station, and converted back in electricity [8–11]. In this manner, seven capital cities from the North Region of Brazil are considered in this research: Belém, Boa Vista, Macapá, Manaus, Palmas, Porto Velho, and Rio Branco. They are the major cities in this region of Brazil, and all of them are located near the Earth's equator. Their privileged geographical position permits that these cites experience roughly 12 hours of sunlight daily. For this reason, cities in the equatorial regions are arguably more suitable for the concept of SBSP.

The goal of this research is to estimate the amount of solar energy collected and transmitted daily by the SBSP. Therefore, a collecting flat surface with a 20% efficiency for the solar panel is assumed, following standard benchmarks for high-efficiency space-grade photovoltaic cells. In addition, power loss in wireless transmission and GEO eclipse is neglected, and the energy collection only occurs when the ground station is illuminated by the Sun. Therefore, the transmission windows is between sunrise and sunset times. Finally, to determine whether a SBSP system could satisfy the energy demand of these cities, the total transmitted solar energy is compared with the annual energy consumption of Belém, Boa Vista, Porto Velho, Macapá, Manaus, Palmas, and Rio Branco, respectively.

2 Methodology and Modeling

This section describes the mathematical and model assumptions employed to calculate the maximum energy collected only by a SBSP system in a GEO orbit and transmitted to seven Brazilian locations situated near the equator.

Firstly, the SBSP's longitude denoted by λ_{SP} is considered equal to $-75°$, the same longitude of the Brazilian Geostationary Satellite SGDC-1. The surface area of the SP is equal to 1 km^2. This value is similar to the SBSP that China plans to lunch by 2030 [12]. On the other hand, the orbital plane (ecliptic) of the Sun is circular and is tilted 23.4° with respect to the equatorial plane of the Earth. Finally, as mentioned previously, the ground station only receives energy between sunrise and sunset times.

In this scenario, the SP generated by the SBSP is given by the following expression [13]:

$$P(\nu) = A\eta S \cos(\nu) K(\nu) \tag{1}$$

where $A = 1$ km^2 denotes the area of the SP, $\eta = 0.2$ is the efficiency of the solar energy collector, $S = 1362$ W/m^2 is the solar irradiance, ν is the incidence angle of the sunlight on the SP, and K is the incidence angle modifier of the solar collector, and defined as [14]:

$$K(\nu) = 1 - b_0 \left(\frac{1}{\cos(\nu)} - 1 \right), \tag{2}$$

where $b_0 = 0.136$ is a dimensionless constant of the panel.

Given the values of the constants A, η, S, and b_0, Eqs. 1 and 2 imply that the power output P depends on the time evolution of the incidence angle ν. This evolution can be estimated by computing ν using the dot product $\langle , \rangle$ between the sunlight vector $\boldsymbol{s}$ and the normal unit vector $\boldsymbol{n}$ to the surface of the solar panel, as illustrated in Fig 1. In this case, by definition,

$$\cos(\nu) = \langle \boldsymbol{n}, \boldsymbol{s} \rangle . \tag{3}$$

The unit vector $\boldsymbol{s}$ of the sunlight with respect to an Earth-centered inertial frame (X_I, Y_I, Z_I) can be stated as

$$\boldsymbol{s} = - \begin{bmatrix} -\cos(\omega_S t) \\ \cos\varepsilon \sin(\omega_S t) \\ \sin\varepsilon \sin(\omega_S t) \end{bmatrix}, \tag{4}$$

where $\omega_S = 0.9863°$/day is the average angular velocity of the Earth around the Sun, and $\varepsilon = 23.5°$ is the inclination of the plane of the ecliptic. Now, the unit vector $\boldsymbol{n}$ is given by the following expression:

$$\boldsymbol{n} = \frac{\boldsymbol{r_{GS}} - \boldsymbol{r_{SP}}}{\sqrt{\langle \boldsymbol{r}_{GS} - \boldsymbol{r}_{SP}, \boldsymbol{r}_{GS} - \boldsymbol{r}_{SP} \rangle}} \tag{5}$$

where $\boldsymbol{r}_{GS}$ and $\boldsymbol{r}_{SP}$ denote the position vectors of the ground station and SP, respectively, as illustrated in Fig. 1. Therefore, the normal to the SP's surface points directly towards the ground station located on the Earth' surface and the SP faces directly towards the Sun to collect uninterrupted solar radiation during daytime.

Now, assuming that the SP position as pointing along the negative X_I-axis, and that the longitude and latitude of the ground station are denoted by λ_{GS} and φ_{GS}, then we have that the position vectors of the SP and ground station can be computed by

$$\boldsymbol{r}_{SP} = - \begin{bmatrix} \cos(\omega_E t) & -\sin(\omega_E t) & 0 \\ \sin(\omega_E t) & \cos(\omega_E t) & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} R + H \\ 0 \\ 0 \end{bmatrix}, \tag{6}$$

$$\boldsymbol{r}_{GS} = R \begin{bmatrix} \cos(\omega_E t) & -\sin(\omega_E t) & 0 \\ \sin(\omega_E t) & \cos(\omega_E t) & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos\varphi \cos\theta \\ \sin\theta \\ \sin\varphi \cos\theta \end{bmatrix}, \tag{7}$$

where $\omega_E = 360.98561°/\text{day}$ is the average angular velocity of the Earth rotating on its axis, $R = 6371$ km is the Earth's mean radius, $H = 35,786$ km is the altitude of a GEO, and $\theta = (-\lambda_{SP} + \lambda_{GS}) + 180°$.

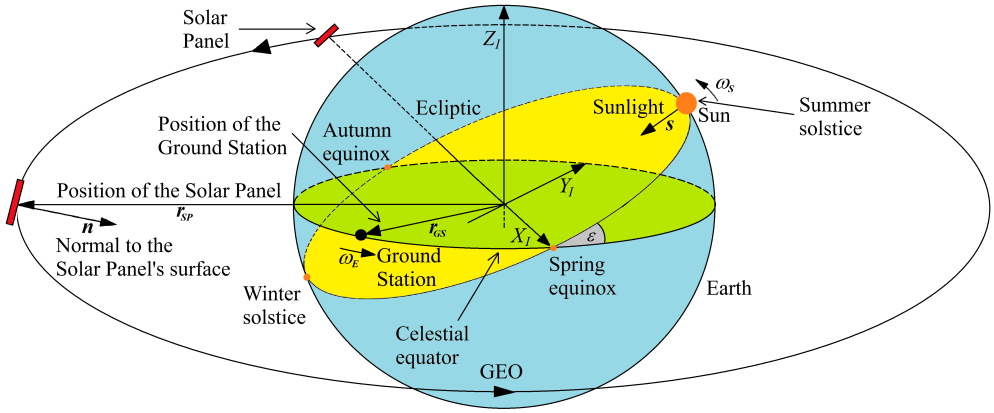


Fig. 1 Illustration of a solar panel placed in a GEO to collect energy and transmit it wirelessly from outer space to a ground-based receiving station. Not to scale.

Finally, to compute the energy E (in GWh) collected in one year by the SBSP, the power out $P(\nu)$ is then integrated over one year, such that $P(\nu) = 0$ before the sunrise (6 : 00 AM) and after sunset (6 : 00 PM) times, that is, $P(\nu) > 0$ if $\cos(\nu) > 0$ and $K(v) > 0$, and $P(\nu) = 0$ otherwise, for every day of the year:

$$E = \int_0^{365} P(\nu)\, \mathrm{d}t, \tag{8}$$

where time t is in days. To compute the energy output in GWh, the integral value of Eq. 8 is then multiplied by a factor of 24 and divided by 10^9.

3 Results and Discussion

Table 1 shows the longitude, latitude, and energy annual consumption of Belém, Boa Vista, Macapá, Manaus, Palmas, Porto Velho, Rio Branco in 2024. Since we model the initial SP and sun positions as pointing along negative X_I-axis and corresponding to the spring equinox, respectively, as illustrated in Fig. 1, then we have that the initial position vectors $\boldsymbol{r}_{SP}$, $\boldsymbol{r}_{GS}$, and $\boldsymbol{s}$ at time $t = 0$ in our model are given by:

$$\boldsymbol{r}_{SP}(0) = \begin{bmatrix} R+H \\ 0 \\ 0 \end{bmatrix}, \quad \boldsymbol{r}_{GS}(0) = R \begin{bmatrix} \cos\varphi \cos(255° + \lambda_{GS}) \\ \sin(255° + \lambda_{GS}) \\ \sin\varphi \cos(255° + \lambda_{GS}) \end{bmatrix}, \quad \boldsymbol{s}(0) = \begin{bmatrix} -1 \\ 0 \\ 0 \end{bmatrix}. \tag{9}$$

Based on the parameters considered into the mathematical model, Fig. 2 shows the power generated profile calculated for a SPBP pointing towards Belém, Boa Vista,

Table 1 Longitude, Latitude, and energy annual consumption of capital cities of the north region of Brazil

Capital city	Longitude (°)	Latitude (°)	Energy Annual Consumption (GWh)
Belém	−48.5039	−1.4558	2583
Boa Vista	−60.6720	2.8208	1376
Macapá	−51.0664	0.0383	1140
Manaus	−60.025	−3.1018	5371
Palmas	−48.3336	−10.1844	531
Porto Velho	−63.9039	−8.7619	930
Rio Branco	−67.8711	−9.9711	623

Source: www.epe.gov.br/pt/publicacoes-dados-abertos/publicacoes/consumo-de-energia-eletrica

Macapá, Manaus, Palmas, Porto Velho, and Rio Branco, respectively, when $t = 0$. As mentioned previously, the first day in our model correspond to spring equinox (March 20-21). As can be noted in Fig. 2, the maximum power is obtained at midday (12:00 PM) when the cosine of the incidence angle ν is approximately equal to 1, this is, the Sun's rays and the normal of the mirror are almost parallel. On the contrary, the transmitted energy is equal to zero at sunrise (6:00 AM) and sunset (6: PM) times, when the Sun's rays are perpendicular to the normal of the SP. In addition, the area below the curve represents the energy output over the spring equinox. Now, Fig. 3 shows the power generation profile along a year of the SBSP pointing towards a ground station located in the capital cities of the North of Brazil. Similarly, the area below the curve represents the energy output over the time. The integral of the curve in Fig. 3 was computed using the Right Endpoint Rule with a step of integration $\Delta t = 0.001$ days.

As can be observed in Fig. 3, the power generated by the SBSP is maximum at spring (March 20-21) and autumn (September 22-23) equinoxes, when the Sun crosses directly above Earth's equator. On the other hand, the power is minimum at summer (June 20-21) and winter (December 21-22) solstices, when the Sun reaches its northernmost (23.5° North latitude) and southernmost point (23.5° South latitude), respectively, and the the Sun's rays and the normal of the mirror are not parallel. Furthermore, the longitudes and latitudes of the ground stations in the capital cities affected very little the daily energy output, such that the energy collected in one year was practically the same for Belém, Boa Vista, Macapá, Manaus, Palmas, Porto Velho, and Rio Branco. This fact arises from the small ratio of the mean Earth's radius (6371 km) to the distance of the SP (42, 157 km).

Finally, Fig. 4 shows the annual demand of energy and annual energy output of the SBSP for the capital cities of the North Region of Brazil. The simulation results show that a SBSP, operating continuously during sunrise and sunset times, permits to generate amounts of energy similar than those achievable by conventional terrestrial systems [15]. In particular, the generation of a SBSP system with a 1 km^2 panel would reached an average of 672 GWh/year, a capacity enough to supply the energy consumption of Palmas and Rio Branco, as shown in Fig. 4. On the other hand,

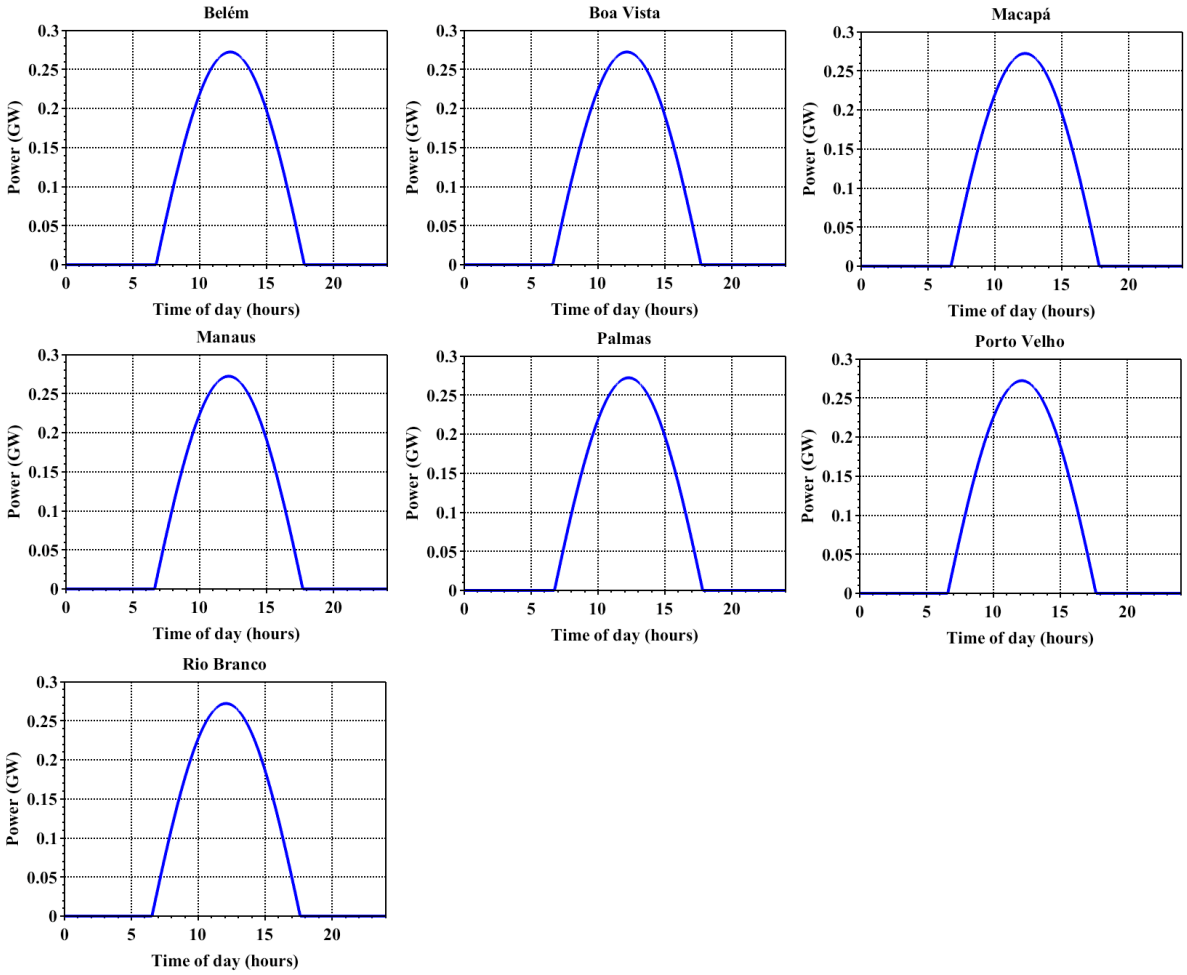


Fig. 2 Power generation profile for spring equinox (March 19-21) of a SBSP pointing towards a ground station located in Belém, Boa Vista, Macapá, Manaus, Palmas, Porto Velho, and Rio Branco. The area below the curve represents the power output over one day.

the annual energy output of the SBSP would not be enough to supply the energy consumption of Belém, Boa Vista, Macapá, Manaus, and Porto Velho. In particular, in cities as Boa Vista, Macapá, and Porto Velho, the collection of solar energy in outer space should be complemented with another kind of clean energy production, including hydroelectric. Now, in Belém and Manaus cities, the implementation of SBSP with a 1 km^2 panel would not be recommended since the energy capacity only corresponds to 26% and 13% of the energy consumption of Belém and Manaus, respectively. In this case, another energy projects should be considered or a SBSP system with a bigger panel, but it will increase the cost of the megaproject. It is important to mention that this amount of energy collected in outer space is possible only in the ideal case,

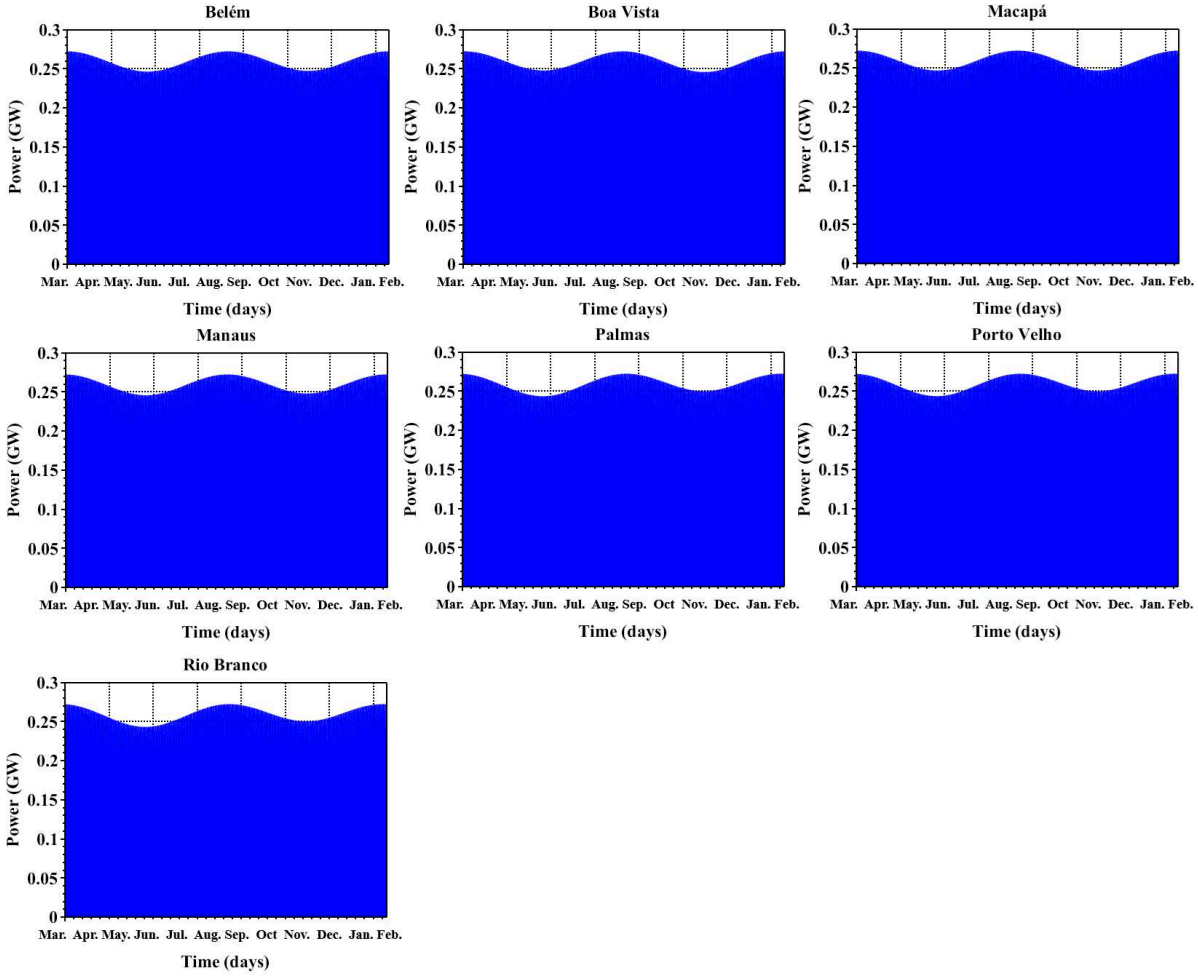


Fig. 3 Power generation profile along a year of a SBSP pointing towards a ground station located in Belém, Boa Vista, Macapá, Manaus, Palmas, Porto Velho, and Rio Branco. The area below the curve represents the power output over a year.

due to we are not modeling power loss in wireless transmission and GEO eclipse is neglected. Therefore, the average of 672 GWh/year is the maximum energy that could be collected by a SBSP with a 1 km^2 panel having an efficiency of 20%.

4 Conclusion

This study showed that SBSP technology has the potential to supply significantly the energy demand of some capital cities of the North Region of Brazil. The proximity to Earth's equator maximizes the efficiency of this concept, making Belém, Boa Vista, Macapá, Manaus, Palmas, Porto Velho, and Rio Branco, ideal candidates

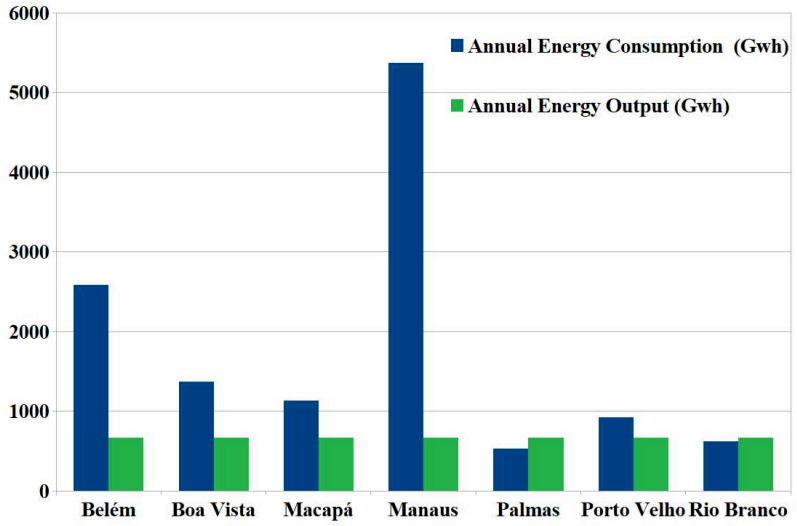


Fig. 4 Annual energy demand and annual energy output of the SBSP for Belém, Boa Vista, Macapá, Manaus, Palmas, Porto Velho, and Rio Branco.

for the pioneer implementation of this technology. On the other hand, although the energy generation of the SBSP system was considerably less than energy consumption in larger urban cities, such as Belém and Manaus, where only the 26% and 13% of the energy demand could be satisfied by this concept, respectively, the system would contribute to reduce significantly the CO2 emissions from energy combustion and industry, confirming the regional sustainability of this technology. Finally, it is important to comment that, in order to improve the accuracy of these results, in future studies, factors as power loss in wireless transmission, GEO eclipses, Moon eclipses, among others, will be considered in our model, so that a more complete set of simulations for SP could be achieved.

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Declarations

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- Ethics approval and consent to participate: Not applicable
- Consent for publication: All authors have read and agreed to the published version of the manuscript.
- Data availability: The data that support the results of this study are available from the corresponding author upon reasonable request.
- Materials availability: Not applicable

- Code availability: The implementations that support the results of this study are available from the corresponding author upon reasonable request.
- Author contribution: Conceptualization, A.F.B.A.P. and F.J.T.S; methodology, A.F.B.A.P. and F.J.T.S; software, F.J.T.S.; validation, A.F.B.A.P. and F.J.T.S; formal analysis, A.F.B.A.P. and F.J.T.S; investigation, A.F.B.A.P. and F.J.T.S; resources, A.F.B.A.P. and F.J.T.S; data curation, A.F.B.A.P. and F.J.T.S; writing—original draft preparation, F.J.T.S.; writing—review and editing, A.F.B.A.P. and F.J.T.S; visualization, A.F.B.A.P. and F.J.T.S; supervision, A.F.B.A.P.; project administration, A.F.B.A.P.; funding acquisition, A.F.B.A.P.

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