LEO SATELLITE-BASED SPACE SOLAR POWER SYSTEMS

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ABSTRACT

In this work, we explore the feasibility of a low Earth orbit (LEO) satellite-based space solar power (SSP) system, where LEO satellites use large photovoltaic (PV) panels to collect solar power and then transmits it to a ground receiver. We establish a theoretical framework to analyze the performance of the considered LEO satellite-based SSP system. Specifically, by taking into account the satellite's rotation angle with respect to sunlight and the mobility of the LEO satellites, we analytically evaluate the solar energy collection through PV panels and quantify the amount of harvested energy by the ground receiver. Our results demonstrate that increasing transmit power of LEO satellites can boost the energy harvesting performance at the ground receiver. Furthermore, by deploying around 100 LEO satellites, a LEO satellite-based SSP system achieves comparable performance to that of a single geostationary orbit satellite-based SSP system.

***Index Terms*—** Space solar power, LEO satellites, wireless power transfer, energy harvesting.

1. INTRODUCTION

The energy problem we are facing today is characterized by the dependence on fossil fuels, climate change, limited energy access, and infrastructure needs, as more than 595 Exajoules of energy is annually consumed worldwide [1]. To manage these challenges, a transition to more sustainable energy sources is required. One potential candidate that addresses these issues is the employment of space solar power (SSP) systems [2]. A typical SSP system consists of a massive satellite, that is deployed on the orbit around the Earth. The satellite is equipped with a large array of solar panels that convert the harvested solar energy into electrical energy. This energy is then transmitted to Earth by using high-powered microwaves which are received by ground-based rectifying antennas and converted back into electricity. SSP systems possess a considerable energy efficiency advantage over terrestrial-based solar power systems, owing to the significantly larger sun exposure time and the immunity of their performance from the weather conditions [3].

The concept of SSP systems was first proposed in [4]. Inspired by this, several SSP architectures have been proposed in the literature [5–7]. For instance, the National Aeronautics and Space Administration (NASA) conducted a study involving a large satellite deployed in geostationary orbit (GEO) equipped with photovoltaic (PV) panels for collecting solar energy [5]. The satellite uses a radio-frequency (RF) microwave to transmit many gigawatts of electricity, which is then collected by a large ground rectifying antenna. More recently, the SunTower was conceptually studied by NASA, which employs an array of concentrator PV elements [6]. One of the key advantages of this design is its flexibility in terms of deployment options. The proposed SunTower satellite system can be deployed in middle Earth orbit, GEO altitudes, or low Earth orbit (LEO) in a sun-synchronous orbit, depending on the specific application requirements. Moreover, the SPS 2000 Japanese model was proposed by the Institute of Space and Astronautical Science (ISAS), which utilizes a LEO satellite equipped with large solar panels to transmit megawatts of power to the ground [7].

LEO satellites are already widely used for a variety of purposes, including communication, remote sensing, and Earth observation [8]. One of the main advantages of using LEO satellites for SSP systems is their closer proximity to Earth compared to other orbiting satellites, such as GEO satellites or lunar bases. This means that the energy transmitted to Earth experiences less transmission loss, thereby making the system more efficient [3]. Despite these advantages of LEO satellites, their high mobility introduces additional challenges on the system implementation. Motivated by this, in this paper, we investigate the feasibility of an SSP system utilizing LEO satellites. More specifically, the main contributions of this work are as follows. First, we analyze the satellite solar energy collection through the PV panels by taking into account the satellite rotation angle with the sunlight. Then, the energy harvested by the ground receiver is quantified by considering the mobility of LEO satellites. Our results indicate that increasing the transmit power of LEO satellites can significantly improve the energy harvesting performance of the ground receiver. Additionally, a LEO satellite-based SSP system can achieve comparable performance to a GEO satellite-based SSP system by deploying around one hundred LEO satellites.

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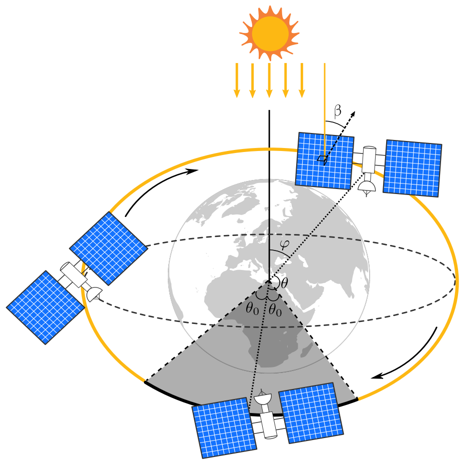

Fig. 1. Illustration of the LEO satellite's orbit.

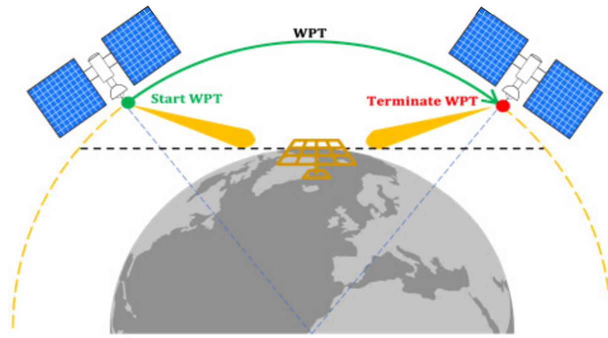

Fig. 2. Illustration of the WPT process.

2. SYSTEM MODEL

We consider a LEO satellite-based SSP system, which consists of N identical LEO satellites evenly deployed on a sun-synchronous orbit as illustrated in Fig. 1. Particularly, the sun-synchronous orbit is characterized by the altitude of LEO satellites, as well as the angle between the orbital plane of the satellite and the sunlight, which are denoted by H and φ, respectively. Each LEO satellite is equipped with a large PV cell array to collect solar energy, while the collected energy is stored in large-capacity rechargeable batteries [9]. Moreover, we consider that multiple large ground rectennas (gRAs) are deployed according to the ground track of LEO satellites' orbits, such that each LEO satellite pass over a gRA every orbit period. Once a LEO satellite pass over a gRA, denoted as *transmission window* , it transmits the collected energy to the gRA via microwave radiation, as illustrated in Fig. 2, which is referred to as the wireless power transfer (WPT) process.

3. SATELLITE ENERGY COLLECTION

In this section, we focus on modeling the output energy of the solar PV panels. We note that the output power of the solar panels is not constant and is affected by the area of the PV cell array, $\mathcal{A}_{\mathrm{s}}$, the efficiency of energy conversion, η_{PV}, and the angle between the sunlight and the normal line of the solar panels. Typically, the satellite's solar panels adopt single-axis solar tracking, which adjusts the angle of the solar panels with the sun as the satellite orbits the Earth, thereby maximizing the amount of solar energy that can be harvested [9]. More specifically, let θ denote the satellite rotation angle from the midpoint of the shaded area, as depicted in Fig. 1. Let β denote the angle between the sunlight and the normal of the solar panels. By adopting the single-axis solar tracking, the minimum achievable β can be expressed as [9, 10]

$$\beta(\theta) = \arccos \sqrt{1 - \cos^2 \varphi \cos^2 \theta}. \tag{1}$$

Furthermore, during each orbit of a LEO satellite, its solar panels collect energy as the satellite moves through areas of direct sunlight. We define $\mathcal{G}_0$ as the solar irradiance per unit area. In the following lemma, we evaluate the total energy collected by each LEO satellite during one orbit period.

Lemma 1. *The energy collected by the solar panels of a LEO satellite for one orbit period is given by*

$$\mathcal{E}_{\mathrm{Solar}} = \int_{\frac{\theta_0}{\omega}}^{\frac{2\pi - 2\theta_0}{\omega}} \mathcal{G}_0 \eta_{\mathrm{PV}} \mathcal{A}_{\mathrm{s}} \beta(\omega t) \mathrm{d}t, \tag{2}$$

where

$$\theta_0 = \begin{cases} 0, \varphi > \arcsin \frac{R_\oplus}{R_\oplus + H} \\ \arcsin \frac{\sqrt{R_\oplus^2 \cos^2 \varphi - (2R_\oplus H + H^2) \sin^2 \varphi}}{(R_\oplus + H) \cos \varphi}, \end{cases} \tag{3}$$

represents the half-angle of the shaded area as shown in Fig. 1, $\omega = \sqrt{\frac{GM}{(R_\oplus + H)^3}}$ *is the angular velocity of the LEO satellite,* G *is the gravitational constant, and* M *is the mass of Earth and* $R_\oplus$ *is the Earth radius.*

Proof. See Appendix A. □

4. WIRELESS POWER TRANSFER

In this section, we analyze the WPT operation from the satellite to the gRA. Typically, the solar energy harvested by the PV panels is stored by the rechargeable batteries and then passes through a direct current to RF (DC-to-RF) converter to generate a microwave of suitable frequency, i.e. f_{RF}. Then, the output power is beamed down to the considered gRA, where it is converted into a usable form. Subsequently, we discuss the RF link efficiency between the transmitting satellite and the gRA, before analyzing the harvested energy by the gRA.

4.1. Microwave Link Efficiency

The size of the transmit and receive antenna apertures plays a crucial role in the design of the microwave link efficiency. In

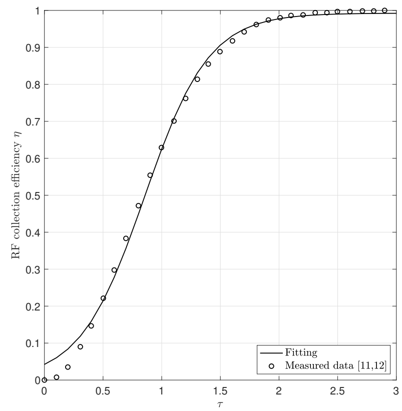

Fig. 3. RF collection efficiency as function of τ.

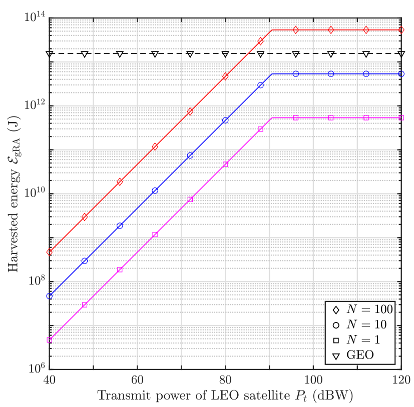

Fig. 4. Harvested energy by the gRA vs. the transmit power of LEO satellites.

general, microwave links are modeled using the Friis transmission equation. However, for microwave power transmission applications, a huge antenna system is required. As a result, the Friis transmission equation is no longer valid [11]. In addition, the relationship between the antenna apertures, wavelength, and distance has only been analyzed empirically [11,12]. Therefore, based on these experimental results, we provide a closed-form expression for the energy collection efficiency of the RF link from the satellite to the gRA, by using curve fitting, as depicted in Fig. 3. More specifically, it is modeled as

$$\eta_{\mathrm{RF}}(r) = \frac{c_1}{c_2 + \exp(-c_3 \tau(r))}, \tag{4}$$

where $\tau(r) = \frac{\sqrt{\mathcal{A}_{\mathrm{t}}\mathcal{A}_{\mathrm{r}}}}{\lambda r}$ represents the normalized antenna apertures, $\mathcal{A}_{\mathrm{t}}$ and $\mathcal{A}_{\mathrm{r}}$ denote the transmit and receive antenna apertures, respectively. Moreover, $\lambda = \frac{c}{f_{\mathrm{RF}}}$ is the wavelength, c is the speed of the light, and r is the distance between the satellite and the gRA. Finally, $c_1 = 0.04417$, $c_2 = 0.0445$, and $c_3 = 3.643$ represent the constants for the fitting function.

4.2. Energy Harvesting Analysis

We consider that each LEO satellite intends to transmit all the collected energy during the *transmission window*. Each LEO satellite transmits energy with a constant transmit power P_t. More specifically, the WPT process starts at the location with the Earth-centered zenith angle $-\phi$ and terminates at the location with the zenith angle ϕ, which are denoted by the green and red points in Fig. 2, respectively. It is worth mentioning that during the WPT process, the satellite's solar panels continue to capture and store energy that can be utilized for energy transmission during subsequent orbital period. Moreover, a LEO satellite can perform WPT only when it is visible from the gRA's position, i.e. the LEO satellite is located above the horizon of the gRA. Hence, the zenith angle ϕ is upper-bounded, i.e. $|\phi| \leq \arccos\left(\frac{R_{\oplus}}{R_{\oplus}+H}\right)$. Therefore, the time for the WPT process of each LEO satellite for one orbit period is given by

$$T_s = \min\left\{\frac{\eta_{\mathrm{DC-RF}}\mathcal{E}_{\mathrm{Solar}}}{P_{\mathrm{t}}}, \frac{2}{\omega}\arccos\left(\frac{R_{\oplus}}{R_{\oplus}+H}\right)\right\}, \tag{5}$$

where $\eta_{\mathrm{DC-RF}}$ denotes the overall efficiency of the DC-to-RF converter. Based on the discussion above, we are now able to provide our main result, i.e. the amount of harvested energy at the gRA during one orbit period, in the following proposition.

Proposition 1. *The amount of harvested energy by the gRA during one orbit period is given by*

$$\mathcal{E}_{\mathrm{gRA}} = 2N \int_0^{\frac{T_{\mathrm{s}}}{2}} P_t \eta_{\mathrm{RF}}(r(t)) \eta_{\mathrm{RF-DC}} \mathrm{d}t, \tag{6}$$

where

$$r(t) = \sqrt{(R_{\oplus}+H)^2 + R_{\oplus}^2 - 2(R_{\oplus}+H)R_{\oplus}\cos(\omega t)},$$

and $\eta_{\mathrm{RF-DC}}$ is the RF-to-DC energy conversion efficiency of the gRA.

Proof. See Appendix B. □

5. RESULTS

We now present the numerical results of the considered LEO satellite-based SSP system. The system parameters are summarized in Table 1. The effect of the transmit power of LEO satellites on the harvested energy by the gRA is shown in Fig. 4. Specifically, we plot the amount of the harvested energy by the gRA for one orbit period, i.e. $\mathcal{E}_{\mathrm{gRA}}$ (J), versus the transmit power of LEO satellites, i.e. P_t (dBW), for various number of LEO satellites, i.e. $N \in \{1, 10, 100\}$. We first notice that the harvested energy by the gRA first increases with an increase in the transmit power of the LEO satellites and then reaches a constant value. This is expected since increasing the transmit power allows each LEO satellite to transmit all of its stored energy to the gRA in a shorter amount of time. Therefore, the LEO

Table 1. System parameters.

Parameter	**LEO** [7]	**GEO** [11]
Altitude (H)	500 km	36000 km
Solar panel size ($\mathcal{A}_{\rm s}$)	1000×1000 m^2	6700×2500 m^2
Satellite transmit antenna aperture ($\mathcal{A}_{\rm t}$)	132×132 m^2	$750^2\pi$ m^2
RF collection efficiency ($\eta_{\rm RF}$)	(4)	75%
Orbit angle (φ)	$\pi/4$	-
Solar irradiance ($\mathcal{G}_0$)	1370 W/m^2	
Gravitational constant (G)	6.67259×10^{-11} m^{3}kg^{-1}s^{-2}	
Mass of Earth (M)	5.9736×10^{24} kg	
Radius of Earth ($R_\oplus$)	6371 km	
Operating frequency ($f_{\rm RF}$)	2.45 GHz	
Ground antenna aperture ($\mathcal{A}_{\rm r}$)	$2500^2\pi$ m^2	
PV energy conversion efficiency ($\eta_{\rm PV}$)	30%	
DC-to-RF conversion efficiency ($\eta_{\rm DC-RF}$)	76%	
RF-to-DC conversion efficiency ($\eta_{\rm RF-DC}$)	70%	

$$r(\Delta t) = \begin{cases} \sqrt{(R_\oplus + H)^2 + R_\oplus^2 - 2(R_\oplus + H)R_\oplus \cos(\phi - \omega\Delta t)}, & 0 \le t \le \frac{T_s}{2} \\ \sqrt{(R_\oplus + H)^2 + R_\oplus^2 - 2(R_\oplus + H)R_\oplus \cos(\omega\Delta t - \phi)}, & \frac{T_s}{2} \le t \le T_s \end{cases} \tag{7}$$

satellite begins transmitting when it is close to the gRA, resulting in a shorter distance between the satellite and the gRA during the WPT process, thus a higher collection efficiency can be achieved. In addition, for scenarios with extremely high transmit power, the LEO satellite transmits all energy immediately, which leads to a constant harvested energy by the gRA. Finally, we numerically evaluate the performance achieved by the GEO-based SSP system [11] for the comparison purpose (denoted by dash lines). It can be observed that increasing the number of LEO satellites can lead to a greater amount of energy harvested by the gRA, resulting in comparable performance to that of a single GEO satellite-based SSP system. This is due to the fact that by having multiple LEO satellites during one orbit period, the gRA can harvest energy from each of them, resulting in a higher overall harvested energy.

6. CONCLUSION

In this work, we investigate a LEO satellite-based SSP system for harvesting solar energy and wirelessly transmitting it to a gRA. We analyze the satellite solar energy collection through PV panels and provide WPT analysis to quantify the performance of the SSP system, where the expression for the harvested energy by the gRA during one orbit period is analytically derived. Our results show that the transmit power of LEO satellites has a significant effect on the harvested energy by the gRA. In specific, increasing the transmit power of LEO satellites boosts the energy harvested by the gRA. Finally, we conclude that deploying a larger number of LEO satellites achieves comparable performance to that of a GEO satellite-based SSP system.

7. APPENDIX A: PROOF OF LEMMA 1

We consider that the LEO satellite is initially located at the midpoint of the shaded area. At time t, the satellite has passed an angle $\theta = \omega t$, where $0 < t < \frac{2\pi}{\omega}$ and the output power of the PV solar panels can be formulated as

$$\mathcal{E}(t) = \begin{cases} 0, & t \le \frac{\theta_0}{\omega} \\ \mathcal{G}_0 \eta_{\rm PV} \mathcal{A}_{\rm s} \beta(\omega t), & \frac{\theta_0}{\omega} \le t \le \frac{\pi}{\omega} \\ \mathcal{G}_0 \eta_{\rm PV} \mathcal{A}_{\rm s} \beta(2\pi - \omega t), & \frac{\pi}{\omega} \le t \le \frac{2\pi - 2\theta_0}{\omega} \\ 0, & t \ge \frac{2\pi - 2\theta_0}{\omega}. \end{cases}$$

Then, by noting that $\beta(2\pi - \omega t) = \beta(\omega t)$ due to the periodicity of the cosine function, and by integrating the output power over one orbit period, the final expression in Lemma 1 is derived.

8. APPENDIX B: PROOF OF PROPOSITION 1

Consider that at time $t = 0$, the LEO satellite starts to transmit power to the gRA. After a period of time Δt ($\Delta t \le T_s$), the Euclidean distance between the LEO satellite and the gRA can be calculated by using the Law of cosines, which is given by (7). Then, the instantaneous harvested power at the gRA is equal to $P_{\rm gRA}(\Delta t) = P_t \eta_{\rm RF}(r(\Delta t))\eta_{\rm RF-DC}$. Hence, the total harvested energy by the gRA from N LEO satellite during one orbit period can be evaluated by integrating the received power $P_{\rm gRA}(\Delta t)$ over the time period $t \in [0, T_s]$ and then multiplying by N, i.e.

$$\mathcal{E}_{\rm gRA} = N \int_0^{T_s} P_t \eta_{\rm RF}\big(r(\Delta t)\big)\eta_{\rm RF-DC} {\rm d}\Delta t. \tag{8}$$

In addition, by noting that $\phi = \frac{\omega T_s}{2}$ and $\cos(\phi - \omega\Delta t) = \cos(\omega\Delta t - \phi)$, the integral range of (8) can be adjusted to $[0, \frac{T_s}{2}]$. Ultimately, the final result in Proposition 1 is obtained.

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