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Power from the Sun: Its Future (Revisited)

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Abstract: Technological advancements must keep pace with earth's rising demand for energy, while minimizing the carbon footprint on earth. One such option is using space based solar (SBS) radio frequency (RF) microwave power beaming. This innovative and novel technology is currently being explored to address terrestrial photovoltaic (PV) intermittency and provide a method to transmit power to other spacecraft in various orbits. This modality of power generation and distribution presents a new way to power terrestrial off-grid applications and earth orbiting spacecraft. In 1968, Dr. Peter Glaser published "Power from the Sun: Its Future", which serves as the foundation of this paper to revitalize scientific interest and efforts in this topic. This paper will primarily focus on the reliance of SBS initiatives on reusable launch vehicles (RLV) to place SBS spacecraft in a designated orbit, as well as the technological, economic, and operational challenges associated with power beaming to earth and other spacecraft. This includes a discussion of the variables from the operational environment that contribute or accelerate spacecraft end of life.

Keywords: space based solar; power beaming; satellite power systems

1. Introduction

The concept of SBS was originally conceived in 1968, by Peter Glaser to convert solar energy and transmit RF energy from space-based solar systems (SBS) to the earth's surface [1]. Initially SBS was proposed as a total solution of the intermittency of solar energy striking the earth. However, with the proliferation of very-low cost terrestrial solar energy, transmission grids covering large areas and different time zones, and development of affordable storage systems, the currently envisioned role for SBS is to complement terrestrial renewable energy applications, by transmitting power to locations lacking sufficient renewable energy resources, as well transmitting energy to spacecraft and space platforms. SBS also permits power beaming to dynamic maritime platforms transiting at irregular times, or other forward operating bases (FOBs) used for temporary operations in remote areas, or permanent operations in locations with low solar insolation. For maritime platforms, a towed or mounted rectifying antenna array could be more resilient than conventional solar harvesting equipment during adverse weather conditions on the high seas. As 71% of the earth is covered in water, the SBS power delivery method using microwaves, that can penetrate through rain or cloud cover, to maritime vessels can prove invaluable.

Over the last several decades, studies have been generated from the Department of Defense (DoD) proposing notional SBS systems and highlighting technological, political, and economic impacts and challenges [2,3]. Technological challenges involve space deconfliction and protection measures from space debris and other satellites, efficient power generation technologies (i.e., DC-to-RF conversion technologies), adequate beaming frequency, and spacecraft survivability; political factors include revision to current space policy and ethics for use of space-based power beaming technology, national security, and militarization potential [2–4]. Economic discussions surrounding the feasibility and success of SBS initiatives are heavily reliant on the proliferation of reusable launch vehicle technology, and the reduction of costs associated with space launch and access to space [5,8].

The original rationale of SBD is to take abundantly available solar energy from space and transmit it through the atmosphere to receiver sites on earth. For this to be possible, a space and

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ground segment must be engineered, whereby a collection of solar energy and conversion from direct current to radio frequency (DC-to-RF) in the microwave region is subsequently transmitted to a rectifying antenna (i.e., a rectenna) for conversion from RF-to-DC. The various stages of the SBS concept and associated conversion efficiencies are shown in Figure 1.

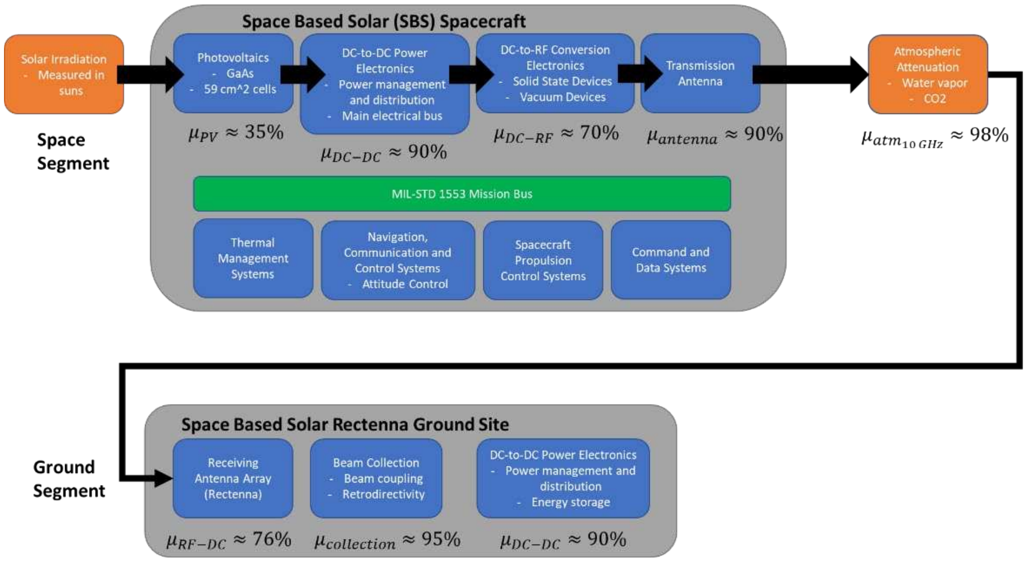

Figure 1. A notional space based solar system (SBS). The system contains a space segment in the form of the sandwich module, with different internal efficiencies, as well as a ground segment for the power beaming receiver site. Projected efficiencies are based on Jaffe and McSpadden, 2013 and Rodenbeck et al., 2020.

The SBS spacecraft energy conversion and beaming stages shown in the upper part of this schematic are being developed as an integrated "sandwich module", as shown in Figure 2 below.

Figure 2. Space based solar sandwich module (left); sandwich step module equipped with more robust thermal radiators. Reprinted from [6,7].

2. US and International SBS Programs

On an international scale, there is a commitment to enhancing and fielding the technology in Europe (i.e., the European Space Agency – ESA) that is not matched in the United States [13]. As it was announced in November 2022, the ESA plans a technical assessment of a GW-scale SBS demonstration by 2040, with funding between 15 to 20 billion euros [13]. ESA's modular design for SBS has been explored for microwave power beaming, with terrestrial demonstrations completed at distances of 36 meters [14]. The ESA SOLARIS program has been deemed "feasible as a complementary power source to terrestrial renewables" [14]. The Japan Aerospace Exploration Agency (JAXA) has a similar roadmap that is investing a multi-billion-dollar SBS effort to develop a 1-GW commercial system by 2035 [15]. The Chinese Academy of Space Technology (CAST) has expressed interest in an SBS demonstration in LEO and GEO by 2050, citing that SBS is "to be China's

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future direction" [12]. Although the People's Republic of China (PRC) has not followed up with any advertised financial commitments for fielding SBS, they have executed testing of microwave power beaming using balloons at altitudes up to 300 meters [14].

Financial commitments from stakeholders can influence the concept of operations (CONOPS), which can dictate where and how often power beaming can take place. This leads to a discussion between customers and stakeholders in SBS initiatives, where the United States and International Partners can come to agreements on which areas to provide power beaming, and when the energy is most needed. These topics tie directly into crucial space law and ethics that require elaboration and collaboration with many nations to provide guidance on SBS system protection, allocation, and integration in the context of national space operations [15]. The space segment is only one portion of the SBS effort, and much effort will need to be conducted to determine the technical and economic challenges when integrating into the existing ground segment, specifically user terminals for command and control (C2), existing space systems architectures, communications with international partners in space (e.g., ESA, Canadian Space Agency, JAXA), and CONOPS development for space vehicle monitoring, telemetry, and tracking.

3. Major Technological SBS Challenges

As mentioned in the Introduction, there are economic, technological, and operational challenges to any SBS development effort, The specific challenges identified in this paper are focused primarily on use of the microwave region for power transmission in the RF spectrum using the SBS sandwich module as the primary vehicle for the satellite conversion system. The following four areas need to be considered before the feasibility of specific design concepts can be determined.

3.1. Orbit Characterization

Determination of the appropriate orbit is essential in optimizing SBS system delivery, as carefully characterization of the orbit can identify perturbations and unwanted time-on-top (ToT) windows (e.g., time overflying a particular region or regions intended for power beaming) that may warrant orbit adjustments. However, the SBS literature lacks the detailed orbital analysis needed for optimizing SBS designs. Detailed orbit analysis is also needed for designing power beaming to other spacecraft in various orbits and multiple terrestrial sites. In general, orbital analysis would be required for SBS feasibility studies, as energy losses occur as a function of beaming distance from source to receiver and varying orbits influence these radii.

Power beaming using the microwave region below 10 GHz allows for penetration of the earth's atmosphere with <5% losses with attenuation attributed to gases, clouds and fog, rain, and tropospheric scintillation [6,7]. Microwave power beaming can be accomplished using 2.45 GHz, 5.8 GHz, and 10 GHz frequencies; however, care should be taken to permit RF deconfliction in commercial communication frequencies in the very high and ultra-high frequency (VHF/UHF) ranges utilized by aircraft and flight controlling agencies [16].

For low earth orbit (LEO), the overflight times over certain geographic areas would be less than 5 minutes for altitudes at 400-1000 km and is not recommended for line of sight (LOS) power beaming. Additionally, spacecraft operating with that small proximity to the earth would be in an eclipse cycle (i.e., not exposed to the sun) every 80-90 minutes. For SBS operating in geosynchronous earth orbit (GEO), the power beam flux density which is a function of distance is significantly lower than that from LEO as, and the losses decay at rapid rates regardless of the beaming frequency [12,14]. Early calculations indicate that the decrease in power density delivered at the ground site will decrease by nearly 99% when shifting from LEO to MEO (400 km to 10000 km). Higher flux densities can be attained using higher frequencies, however the propagation losses due to the earth's atmosphere are also more prevalent above 10 GHz. Therefore, the objective is to find the "goldilocks zone" which seeks to mitigate the short overflight times, power beaming flux density losses over longer distances, and earth-space propagation losses.

We propose to develop a constellation that uses multiple satellites operating at 7000-10000 km in medium earth orbit (MEO), to maximize the continuous and uninterrupted power received at terrestrial sites. For example, Figure 3 below illustrates a 24-spacecraft constellation, with three different inclination angles (non-polar orbit), where there are 8 spacecraft per inclination capable of overlapped power beaming to multiple ground stations. This ensures that each site receives a minimum of 6 and maximum of 9 spacecraft power beaming at any given time anywhere on the earth.

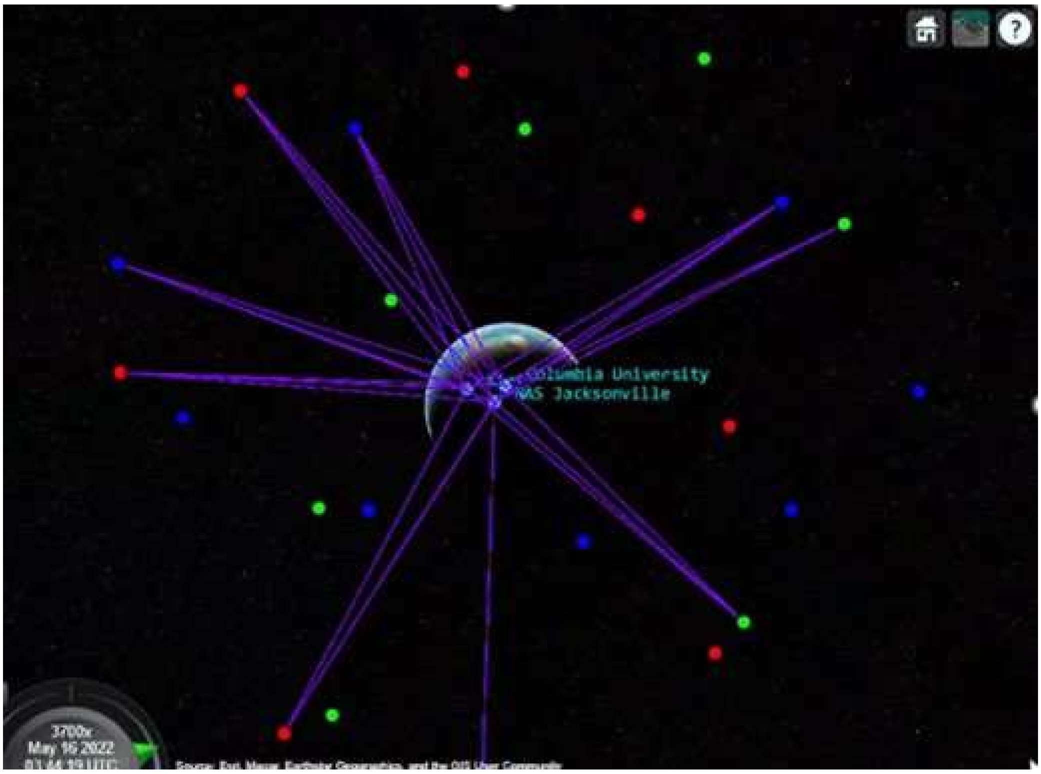

Figure 3. SBS proposed constellation to promote continuous uninterrupted power with a minimum of 6 spacecraft capable of power beaming to any site on earth; created using the MATLAB Aerospace Toolbox v2022a.

3.1.1. Orbital Challenges

LEO is becoming increasingly congested due to saturation of commercial communications satellites, coupled with existing orbital debris [17,18]. Any spacecraft intending to operate in LEO would have to consider the probability and negative impacts of physical contact between manmade orbiting objects, in addition to the existing probability of celestial threats posed to spacecraft in orbit (i.e., micrometeorites). For the proposed SBS system intended to deliver power on the megawatt scale, the surface area reaches up to 1300 m2, which increases the threat of potential debris strikes [19]. Using a MATLAB Aerospace Toolbox Orbit Propagator, it is possible to calculate the various ToT for power beaming, comparing LEO, MEO and GEO; MEO and GEO results are shown in Figure 4 below. Operating the SBS constellation in LEO is not practical based on time on top and overflight characteristics. LEO overflight time simulations for a designated area in a 24-hour period are shown to be approximately 0.3 hours, whereas MEO and GEO provide 6.93 and 10.1 hours respectively. The overflight time is directly related to the ability of an SBS satellite to provide wireless power transmission to that location, therefore short overflight times provided by LEO are undesirable.

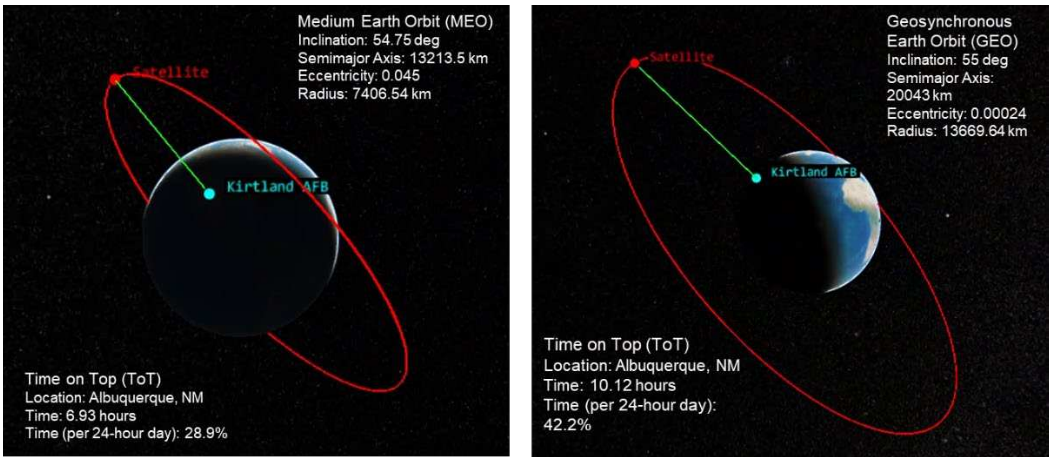

Figure 4. Simulated trajectory of a single SBS satellite conducting RF microwave power beaming to a ground station for both MEO and GEO; created using the MATLAB Aerospace Toolbox v2022a.

3.1.2. Getting to Orbit: Launch Vehicle Reusability and Reliability

One of the areas identified by Glaser is the orbit characterization, however the use of launch vehicles to achieve a particular orbit is not discussed. In recent years, the use of reusable launch vehicles (LV) to deliver satellites into LEO has become more prolific. The reusable rocket booster from SpaceX utilizing Falcon-9 provides a whole new metric for placing spacecraft into specified orbits. For single launches to LEO, Falcon-9 price per kg (ppkg) has decreased from 2009 to 2022 at $3516/kg to $2900/kg respectively; this includes an 8% increase due to inflation from SpaceX in 2022 [20,21]. Despite the decreasing ppkg, the current launch costs do not yet match the forecasted orders-of-magnitude reduction made in 2016, which claimed Falcon Heavy at $951/kg in 2020; Falcon Heavy is reported at ~$1500/kg as of 2022 [4,17]. According to the Center for Strategic and International Studies (CSIS) Aerospace Security Project in collaboration with the National Defense and Johns Hopkins Universities, stated cost saving practices for space launch include exploration of LV partial reusability as a more cost-effective method, and avoiding fixed costs associated with maintaining a ground-based spaceport through utilization of an air- or sea-based launch platform [5,22].

Ppkg estimates use data unique to each LV on dedicated launches, with "launch cost" definitions subject to interpretation. Reported ppkg estimates assume unit flyaway cost, which "includes all direct and indirect manufacturing costs and their associated overhead plus recurring engineering, sustaining tooling, and quality control", and associated testing, engineering, manufacturing and tooling [8]. Based on this broad definition, projected and actual launch ppkg metrics can vary, however the simplest method for calculating ppkg is dividing the launch cost by the payload capacity; small-lift and heavy lift LVs can carry 2000 kg and 20,000 kg to LEO respectively [23]. Some subsequent questions for economics of reusability include determination of (1) how many launches can be reliably conducted to amass the SBS constellation, (2) what is the Falcon-9 LV reliability to achieve higher orbits outside low earth orbit (LEO) into medium earth orbit (MEO), and (3) does the price change for each subsequent launch now that the booster is considered "used". If reliability and maintainability (R&M) engineering practices are followed for the booster, then the reliability of the component may be restored to "like new" condition, but the reliability may still be less with every subsequent launch to individual component variability [24]. This is especially true when considering the end of life (EOL) characteristics associated with sensitive electronics components after exposure to violent launch vibrations and temperatures [26].

To provide some context, Department of Defense (DoD) customers may be more risk averse to utilize boosters for subsequent launches due to conditional reliability concerns. This may have an influence on the price per launch, and as a result the total cost per kilogram of material launched. An analogous scenario would be purchasing a new car with no miles at a higher price, versus saving money by purchasing a used car with more miles on the engine; both cases present an inherent level of risk based on the perceived confidence in the system. The conditional reliability for reusable boosters needs to account for critical factors that contribute to not only system confidence, but also system R&M [25]. The success of fielding SBS beyond LEO is dependent on the cost reduction resulting from the LVs. The LV technology must be resilient and survivable after repeat launches, and use of R&M engineering principles can help enhance the system confidence. Additionally, it can help identify improvements in the booster technology repair processes by analyzing for most efficient (for time and cost) preventative maintenance intervals and providing more accurate component failure rates as successful launches become more frequent. This application would also be applicable to various LV technologies such as cryogenic boosters currently employed by Blue Origin on the BE-4 engine [27]. The cryogenic booster technology is employed by the Blue Origin New Glenn program to maximize reusability and availability through use of cleaner fuel and can operate for a minimum of 25 flights. Additionally, the liquid hydrogen powered upper stage can deliver payloads over 13000 kg to geostationary transfer orbit (GTO), the intermediate orbit before maneuvering the satellite into GEO. SpaceX Falcon-9 can launch 8300 kg to GTO, at $67M/launch, when compared to the New Glenn anticipated launch costs at $20M/launch, Blue Origin could have a unique opportunity to conduct launches solely for SBS satellite deployment in GEO.

3.2. Solar Energy Conversion Devices

Current technology for consideration in SBS missions will be flight proven hardware (i.e., equipped and utilized on existing satellites), which includes triple junction Gallium Arsenide (GaAs) cells. Some challenges for solar energy conversion devices are identified as reduction of manufacturing costs, improving collection and conversion efficiencies, and improving survivability in harsh environmental conditions, such as various orbits in space [1]. A major challenge for SBS will be competing with the existing terrestrial commercial market to be viable. This means the challenges identified above must be addressed prior to any large scale SBS buildup in any orbit. One area for improvement in SBS system performance and reliability would be a uniquely tailored SBS space radiation damage assessment based on the orbit and associated radiation zone in which the satellite(s) are intended to operate. This would promote system longevity and provide options for SBS users to maximize power beaming opportunities.

3.2.1. Technical Challenge: Spacecraft Radiation-Induced Degradations

Calculation of radiation exposure in the form of high energy particles for SBS spacecraft operating in MEO is essential for determination of EOL. A benefit from one analytical method in [28] illustrates and quantifies the high energy proton and electron regions within the Van Allen belts, along with the quantitative methods to calculate the duration exposure and energy magnitude. This analytical tool is beneficial to visualizing and understanding spacecraft radiation exposure in various orbits (i.e., MEO and GEO) which will be subjected to highly energized (~10^2 eV to >10^6 eV) particle bombardments; this particle-matter interaction can be explored further to calculate potential accelerations of electronic systems damage resulting in decreased spacecraft lifespans [29].

3.3. Power Beaming Transmission Technology

The primary literature pertaining to the SBS technology itself is disseminated largely through terrestrial power beaming science in physics journals, with the RF propagation technique using phased arrays coupled with PV arrays and DC-to-RF power electronics [7,30]. The science of power beaming, for both terrestrial and space-based applications, is concentrated on laser and microwave power transmission; this paper will focus on the technology and operations pertaining to microwave power transmission. A modular approach using the sandwich module is different than the approach taken by the European aerospace company Airbus, which involves solar concentrators to deflect sunlight onto a single RF transmission module [13]. While there is debate on how to provide consistent power most efficiently to the SBS for conversion, modularity and lowered RLV costs will enhance the economic feasibility of SBS [12,13,15,31]. To conduct power beaming, continuous wave

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amplifiers are coupled with a phased array antenna to emit microwaves. These amplifiers are connected electrically between the solar energy collector and are assumed to be ~90% efficient at the antenna, with DC-to-RF efficiencies in the range of 30-45%. These driver-stage and final-stage amplifiers can be used to generate microwave radiation to transmit power, where for a 2.99 GHz frequency, a 2-km diameter transmission antenna could irradiate an area of ~7 km^2 [1].

3.3.1. Earth-Space Propagation Losses

It is pertinent to justify the altitude change for SBS to higher orbits to (1) deconflict with LEO debris and congestion, and (2) optimize time on top for power beaming. As a result of the increased distance from emitter to receiver, and the microwave power beaming frequency, this requires an exploration of how the earth's atmosphere impacts the ability to deliver continuous uninterrupted power to an area. This analysis indicates two possible areas for further study, (1) how the angle of the receiver and emission source phased array antennas contributes to overall system power generation and performance (i.e., how well aligned the antennas are when considering beta angles), and (2) the specific frequencies that are most beneficial for microwave power beaming (i.e., use of 2.45 GHz, 5.8 GHz, or 10 GHz) [6,28,32]. Assuming that SBS will be accomplished using frequencies < 10 GHz, the power density passing through the atmosphere would be < 1 W/cm^2. As the microwave beam passes through the atmosphere, scattering can occur which can result in power flux density losses, however the losses for frequencies above 10 GHz is < 5%, with atmospheric ionization unlikely to occur due to the low voltage gradient [1,6,7].

3.4. Ground Receiver Stations

There is a relationship between the size of the transmission antenna correlated to the size of the receiver antenna, where the rule of thumb is that the receiver site needs to be larger when using microwave power beaming. Using the example listed above, for a microwave system beaming 2×10^7 kW from a 3.1 km^2 antenna to the 7 km^2 receiver site, the microwave beam power density would be < 1 W/cm^2. This example provides some context as to the size of the receiver site for the rectifying antenna (i.e., receiver antenna), as well as the safety precautions needed to be taken and the power storage and distribution methods used at the site.

Due to the large SBS system array size, and high costs associated with formation of the large array, time on top (ToT) is an essential factor for identifying if the orbit is satisfactory for power beaming operations where longer dwell times are preferred. Since the initial orbital analysis was accomplished using a 1-ball constellation (e.g., a single SBS spacecraft in a single orbit), it will be necessary to develop a constellation of multiple SBS spacecraft to ensure 24-hour access to power beaming. Using the global positioning system (GPS) as a similar system that enables users 24-hour access to positioning capability, with overflight of terrestrial ground sites reliant online-of-sight (LOS), it is possible to generate a modified SBS constellation to provides access to power beaming (such as the one shown in Figure 3). The receiver sites would need to be equipped with rectifying antennas to convert the RF energy to DC and be in a position that permits an unobstructed view of the sky. The specific number of SBS spacecraft required would be based on the desired power requirements at the receiver site(s), where each orbit would have distinct advantages and disadvantages.

Since ToT is to be maximized, LEO is not considered a viable candidate as the short orbital periods (~90 minutes based on <2000 km altitudes) only allows for brief overflight of the receiver location. As a result, this would require more spacecraft and a larger constellation to support 24-hour continuous coverage of one receiver site. Multiple receiver sites are considered, but this would require the SBS spacecraft to conduct power beaming operations to multiple sites simultaneously and conduct beam steering methods while orbiting. An important consideration for terrestrial site determination would be surface area needed on the ground for receiving the energy from the SBS; according to Glaser [1], the rectenna area for receiving beam from SBS on GEO, would be 1.5 times greater than the area of the satellite unit. According to Vigliarolo, 2022, [14], a 10 times larger area would be needed on earth. We note that this area ratio depends on numerous factors that may have been omitted from initial analyses, which includes (but not limited to) the power beaming transmission distances, relative angles of emitter-to-receiver antennas, earth-space propagation losses, the number of satellites beaming on the same rectenna, and beam divergence. As each rectenna could receive beams from several satellites at different times, its size may be best be estimated from a safety threshold of RF beaming through the lower atmosphere and on the ground. Further research is needed for optimizing the sizes of the ground receivers.

Based on the orbital characteristics, MEO and GEO are more practical candidates for SBS power beaming, however the specific impacts to power beaming performance due to increased radii from emitter to receiver need to be considered. Also an important aspect is determining the SBS system end of life (EOL), more specifically what to do with the spacecraft once it is no longer able to complete its mission. EOL options may include inducing a velocity (e.g., through thermal runaway on the lithium batteries) to elevate the orbit to higher altitudes outside earth's gravity or allow the satellite to succumb to atmospheric drag and burn in the atmosphere [6,14,33].

3.4.1. Technical Challenge: Do no harm Initiatives

According to Glaser, "the problem of safety should be no more difficult than that of highway and air traffic control", but the microwave power densities might damage objects or living tissues that entered the beam [1,6]. This is also dependent on the frequency being used, as well as the exposure duration times. It is recommended that the beam itself does not utilize harmful power densities and frequencies unsafe for prolonged human exposure. Additionally, it is recommended that safety devices be used to track and monitor power densities with regulations established and enforced to prevent damage to humans, aircraft, avian wildlife, and the environment. According to [34], reference levels for electric field strength, magnetic field strength, and power density in controlled environments are tabulated with various frequency ranges. Of note, for 10 GHz power beaming operations, a power density of 50 W/m^2 yields a reference period of 6 minutes for safe human exposure. However, future studies to determine power density thresholds for safe continuous power beaming operations to prevent harm to humans and the environment is recommended for SBS operations and receiver antenna design.

4. Conclusions

SBS systems are capable of continuous power delivery during day or night operation and can be coupled with terrestrial PV collection methods to further the receiver site electricity generation. The development of SBS systems can complement earth-based solutions for mitigating climate change and can also power a variety of space operations. When considering the economics of SBS, modularity of the SBS system coupled with reductions in launch vehicle costs are critical to the successful adoption of space solar power. It is recommended that if time for fielding the technology is a critical factor, that the United States and International partners (e.g., ESA) begin collaboration to the maximum extent practicable to share lines of effort to accelerate operational use of SBS]. The continued research of SBS "may help lead the world into an era in which an abundance of power could free man from his dependence on fire" [1].

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Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Glaser, P.E. Power from the Sun: Its Future. Science **1968**, 162, 857-861.
2. Bain, C. N. Satellite Power System (SPS) Military Implications. Report Number: HCP/R-4024-11. U.S. Department of Energy, Office of Energy Research, Washington, D.C. Available online: https://www.osti.gov/servlets/purl/6187178 (December 2023).
3. Jones, H. W. (2018). The Recent Large Reduction in Space Launch Cost. In Proceedings of the 48th International Conference on Environmental Systems, Albuquerque, New Mexico, USA, 8-12 July, 2018.
4. Williams, I., Dahlgren, M., Roberts, T. G. & Karako, T. Boost-Phase Missile Defense: Interrogating the Assumptions. Available online: Center for Strategic and International Studies, Washington, DC. https://csis-website-prod.s3.amazonaws.com/s3fs-public/publication/220624_Karako_BoostPhase_MissileDefense.pdf (December 2022).
5. Harrison, T.; et al. (2017, March). Implications of Ultra-Low-Cost Access to Space. Center for Strategic and International Studies, Washington, DC. Available online: https://www.csis.org/analysis/implications-ultra-low-cost-access-space 9 (December 2022).
6. Rodenbeck, C. T., Jaffe, P. I., Strassner, B. H., Hausgen, P. E., McSpadden, J. O., Kazemi, H., Shinohara, N., Tierney, B. B., DePuma, C. B., & Self, A. P. Microwave and Millimeter Wave Power Beaming. *IEEE Journal of Microwaves* **2020**, 1, 229-259. Available online: https://doi.org/10.1109/JMW.2020.3033992.
7. Jaffe, P. I., & McSpadden, J. O. Energy Conversion and Transmission Modules for Space Solar Power. *Proceedings of the IEEE* **2013**, 101, 1424-1437. Available online: https://doi.org/10.1109/JPROC.2013.2252591.
8. United States Energy Information Administration. Electricity explained: Use of electricity. Available online: https://www.eia.gov/energyexplained/electricity/use-of-electricity (18 December 2023).
9. National Renewable Energy Laboratory. Best Research-Cell Efficiency Chart. Available online: https://www.nrel.gov/pv/cell-efficiency.html (November 2023).
10. Engel, J. EIA: Global renewable energy consumption nearly reaches that of liquid fuels by 2050. Available online: https://www.renewableenergyworld.com/policy-regulation/eia-global-renewable-energy-consumption-nearly-reaches-that-of-liquid-fuels-by-2050/ (October 2023).
11. Center for Sustainable Systems, University of Michigan. U.S. Energy System Factsheet, Pub. No. CSS03-11. Available online: https://css.umich.edu/publications/factsheets/energy/us-energy-system-factsheet (April 2023).
12. Ernst, D. Beam It Down, Scotty: The Regulatory Framework for Space-Based Solar Power. *Reciel* **2013**, 22, 354-365. ISSN 2050-0386.
13. Clery, D. Has a new dawn arrived for space-based solar power? *Science* **2022**, 378, 238-239. Available online: https://doi.org/10.1126/science.adf3948 (August 2023).
14. Vigliarolo, B. Proof of Concept for Satellites Beaming Energy to Earth. Available online: The Register, Science. https://www.theregister.com/2022/11/10/esa_space_based_solar_power/ (December 2022).
15. Caton, J. L. Space-Based Solar Power: A Technical, Economic, and Operational Assessment. Available online: Strategic Studies Institute, US Army War College. https://www.jstor.org/stable/resrep11703 (April 2023).
16. Canada Federal Department of Health. Limits of Human Exposure to Radiofrequency Electromagnetic Energy in the Frequency Range from 3 kHz to 300 GHz. Safety Code 6 Report from the Consumer and Clinical Radiation Protection Bureau, Environmental and Radiation Health Sciences Directorate Healthy Environments and Consumer Safety Branch, Health Canada. Available online: https://www.canada.ca/en/health-canada/services/publications/health-risks-safety/limits-human-exposure-radiofrequency-electromagnetic-energy-range-3-300.html (January 2023).
17. Future Timeline. Launch costs to low Earth orbit, 1980-2100. Available online: https://www.futuretimeline.net/data-trends/6.htm (January 2023).
18. Peters, A. & Salehfar, H. Spacecraft Solar Electric Propulsion (SEP) Power Conservation Methods. In Proceedings of the AIAA Propulsion and Energy 2020 Forum. Available online: https://doi.org/10.2514/6.2020-3536 (April 2023).
19. Wang, B. Space Based Solar Power 10 Watt Demos in Space Now and Beaming and Other Demos Now to 2023. Available online: https://www.nextbigfuture.com/2021/04/space-based-solar-power-10-watt-demos-in-space-now-and-beaming-and-other-demos-now-to-2023.html (February 2023).
20. Wall, M. SpaceX Raises Launch and StarLink Prices, citing Inflation. Available online: https://www.space.com/spacex-raises-prices-launch-starlink-inflation (May 2023).
21. Clark, S. SpaceX Launch Sets Record for Falcon 9 Payload Mass. Available online: https://spaceflightnow.com/2022/08/27/falcon-9-starlink-4-23-live-coverage/ (August 2023).
22. Stockdale, P. Aughenbaugh, S. & Boensch, N. Low-Cost Access to Space: Military Opportunities and Challenges. National Defense University, Defense Horizons 83, February 2018. Available online: https://inss.ndu.edu/Portals/68/Documents/defensehorizon/DH-83.pdf (February 2023).
23. Roberts, T. G. Space Launch to Low Earth Orbit: How Much Does It Cost. Available online: https://aerospace.csis.org/data/space-launch-to-low-earth-orbit-how-much-does-it-cost/ (September 2023).

doi:10.20944/preprints202402.0147.v1

24. Ebeling, C. Time-dependent failure models. In *An Introduction to Reliability and Maintainability Engineering*, 2nd Ed. Waveland Press: Long Grove, IL, USA, 2010.
25. Ebeling, C. Maintainability. In *An Introduction to Reliability and Maintainability Engineering*, 2nd Ed. Waveland Press: Long Grove, IL, USA, 2010.
26. Aerospace Corporation. Novel Satellite Deorbiting Method Can Help Mitigate Space Debris Crisis. Available online: https://aerospace.org/node/46996/printable/print (August 2023).
27. Berger, E. Rocket Report: SLS boosters may expire in December; Blue Origin delivers the BE-4s. Available online: https://arstechnica.com/science/2022/11/rocket-report-sls-boosters-may-expire-in-december-blue-origin-delivers-the-be-4s/ (November 2022).
28. Karandikar, A. Studying the Van Allen Belts with Particle Tracing Simulation. Available online: https://www.comsol.com/blogs/studying-the-van-allen-belts-with-particle-tracing-simulation/ (May 2022).
29. Vette, J.I. The AE-8 Trapped Electron Model Environment, NSSDC/WDC-A-R&S 91-24, 1991a. Available online: https://www.spenvis.oma.be/help/background/traprad/traprad.html#TREPOP (April 2023).
30. Schmitt, R. N., Prado, A. F., Sukhanov, A., & Gomes, V. M. Swing-By Applications and Estimation of the Van Allen Belts' Radiation Exposure for a Spacecraft in a Low Thrust Transfer to the Moon. *Symmetry* **2022**, 14. Available online: https://www.mdpi.com/2073-8994/14/3/617/htm (February 2022).
31. Rubenchik, A. M., Parker, J. M. Beach, R. J. & Yamamoto, R. M. Solar Power Beaming: From Space to Earth. U.S. Department of Energy Report LLNL-TR-412782, Lawrence Livermore National Laboratory.
32. Mathworks. Matlab Aerospace Toolbox Reference and Documentation. Available online: https://www.mathworks.com/help/aerotbx/index.html (December 2022).
33. Wertz, J.R., Everett, D.F., & Puschell, J.J. Space Mission Engineering: The New Smad. Hawthorne, CA, USA. Microcosm Press, 2011.
34. Health Canada. Limits of Human Exposure to Radiofrequency Electromagnetic Energy in the Frequency Range from 3 kHz to 300 GHz. Available online: https://www.canada.ca/en/health-canada/services/publications/health-risks-safety/limits-human-exposure-radiofrequency-electromagnetic-energy-range-3-300.html.