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Evolving Markets, Capabilities, and CONOPS for Economically Competitive Space Solar Power

By John C. Mankins

Abstract

Several new capabilities, market opportunities, and concepts have emerged during 2021–2022 that will improve prospects for economically feasible, hyper-modular space solar power (SSP) systems. These include launch options, carbon-driven pricing, and more sustainable concepts of operations (CONOPS) for both space and ground segments. First, SpaceX has announced expected launch rates and costs, and an operations schedule for its planned Starship+ Heavy Booster launch system. Other countries and companies, including Blue Origin, China, Japan, the European Space Agency, Honda, and Rocket Lab in New Zealand have also announced plans for reusable launchers. It now seems inevitable that low-cost space access is coming before the end of this decade. In addition, multiple countries have announced ambitious carbon net-zero goals. However, in late 2021 at the COP26 meeting in Glasgow, UK, it was evident that there is no easy solution to carbon emissions driving climate change. Thus, carbon policy-driven pricing on low emissions technologies, such as SSP, seems likely, which will dramatically increase their economic attractiveness, perhaps reducing their perceived risks Lastly, there is continuing concern regarding orbital debris and operations risks to SSP. There are several new concepts and CONOPS that can improve expectations for future SSP systems.

Keywords: Space solar power, SSP, IAA, SPS–ALPHA

Introduction

Several new capabilities, changing market opportunities, and novel concepts have emerged during 2021–2022 that will positively impact prospects for economically feasible, hyper-modular space solar power (SSP) systems. These include (1) launch options, (2) carbon-driven pricing, and (3) more sustainable concepts of operations (CONOPS) for both the space and the ground segments. First, expected launch rates and costs, and a schedule to begin operations have now been announced by SpaceX for its planned Starship+ Heavy Booster reusable two-stage-to-orbit (TSTO) launch system. At the same time, a number of other countries and companies, including Blue Origin (from prior planning), China, Japan, the European Space Agency (ESA), Honda, and even Rocket Lab in New Zealand have all announced plans to follow with their own reusable launchers. It seems now inevitable that truly low-cost space access is coming—and before the end of this decade. In addition, ambitious carbon net-zero goals have been announced by multiple countries during the past two years or so. However, in late 2021 at the COP26 (Conference of the Parties) meeting in Glasgow, Scotland (UK) it was evident that there is no easy solution to the challenge of carbon emissions driving climate change. As a result, the prospects now appear likely for carbon policy-driven pricing on low emissions technologies, such as SSP, that will dramatically increase their economic attractiveness, making it more likely that the perceived risks in such new technologies can be overcome. Lastly there is continuing concern regarding orbital debris and operations risks that must be addressed by SSP proponents for SSP to be realized. There are a number of new concepts and CONOPS that can improve expectations for the operations of future SSP systems.

This paper reviews the changes of the past several years, and frames an integrated view of how they impact the technical viability and economic viability of modular SSP systems such as SPS–ALPHA (solar power satellite by means of arbitrarily large phased array).

SPS–ALPHA Overview

SPS–ALPHA (Figure 1) was first studied under a NASA advanced innovative concepts program Phase 1 concept study published in 2011.[1] Further development of the concept has occurred since that study, of course.[2] The following paragraphs provide an overview of the concept as it stands now.

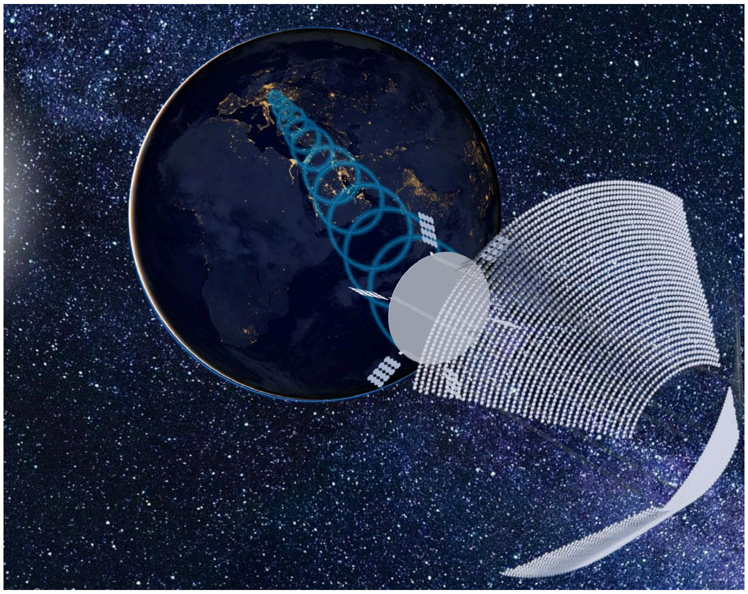

Figure 1: SPS–ALPHA transmitting energy to Europe at midnight. (Concept and image courtesy John C Mankins.)

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[1] John C. Mankins, *SPS–ALPHA: The First Practical Solar Power Satellite* (Washington, DC: NASA Institute for Advanced Concepts, 2011).

[2] John C. Mankins, *The Case for Space Solar Power* (Houston: Virginia Edition, 2014).

Core Technical Aspects

The core technical aspects of the SPS–ALPHA concept have remained unchanged, although various specific aspects of the design have evolved—from the Mark 1 to the Mark 2 and finally to the Mark 3. These involve both component- and architecture-level features. The most important component-level aspects include the following.

(1) First, the use of microwave frequencies (i.e., in the range from 2 to 10 GHz) for wireless power transmission to achieve all-weather operations and a simple very high-efficiency rectifying antenna (rectenna) receiver.
(2) Also, a reliance on solid-state power amplifiers and retrodirective phase control to provide precision electronic pointing of the microwave wireless power transmission from transmitter to receiver—essentially trading phase information and control for physical rigidity and the pointing of the transmitter.
(3) In addition, the presumption of high-efficiency radiation-tolerant photovoltaic arrays to convert sunlight into electrical voltage—feeding into a local, low-voltage power management and distribution system and driving the solid-state power amplifiers.
(4) A reliance on the capabilities of modern electronics and software—including systems autonomy, sensors of various sorts, onboard data processing and storage, resilient and reconfigurable network computing, etc.—to enable the platform to self-assemble, self-repair and self-reconfigure without the intervention of either astronauts or substantial external infrastructures.
(5) Use of designs, materials, and components to enable distributed local mitigation of what would normally be system-level disturbances or effects—including disposal of waste heat and compensation for and/or suppression of structural vibrations.
(6) Use of high-efficiency propulsion systems for attitude control and to assist with structural controls and vibration suppression, including both electric thrusters involving benign propellants (e.g., Hall thrusters) or solar pressure (e.g., solar sails).

In addition, the most important architecture-level aspects (enabled by the component technologies above) include:

(7) The employment of a hyper-modular architecture—now well-known in SPS circles, but first introduced by SPS–ALPHA—which enables exceptionally large platforms to be assembled from very larger numbers of relatively very small, mass-produced modules.
(8) Employing heliostats (i.e., reflectors) on a relatively low-mass structure to redirect incoming sunlight adaptively toward the photovoltaic array—thereby enabling a

planar hyper-modular energy conversion array to deliver power to a remote receiver almost continuously, rather than only when the alignment is correct.

(9) Use of a planar mesh antenna as the receiver (aka a rectifying antenna, or rectenna) on shore or off at an elevation of at least 3–4 meters, and up to 5–10 meters—allowing dual use of the area underneath. For example, allowing the use of land underneath the rectenna for agriculture. Moreover, if lighter in color (i.e., with a higher albedo) or reflecting, then there can be a net a cooling effect based on the fill-factor of perhaps 15%–20%.

(10) Integration of energy storage systems at the site of each receiver, allowing a single SPS to deliver continuous power to multiple sites through the use of the local energy storage for time sharing. For example, 2 GW of delivered power from a single SP–ALPHA can be shared among multiple ground sites through the use of energy storage.

SPS–ALPHA Space Segment[3]

As Figure 2 shows, the SPS–ALPHA space segment comprises four major elements: (A) the energy conversion array, (B) the heliostat reflector array, (C) connecting structures between (A) and (B), and (D) additional modules, such as attitude control modules.

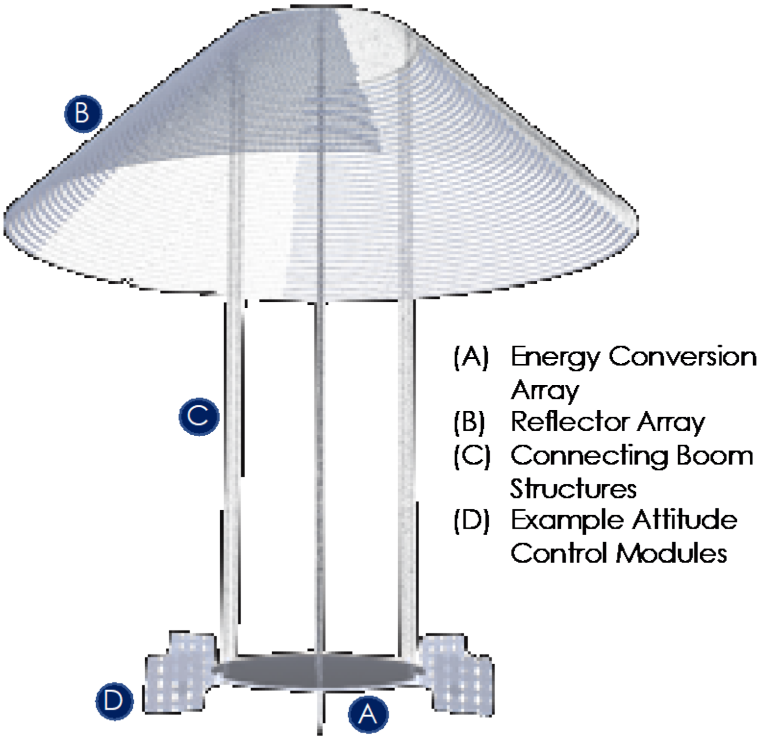

Figure 2. SPS–ALPHA (Mark-3) Space Segment

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[3] The discussion here addresses the SPS–ALPHA Mark 3 version, first presented in 2020.

Supporting Infrastructure

The single most critical element of supporting infrastructure for any SSP system—including SPS–ALPHA—is, of course the Earth-to-orbit (ETO) transportation system. The single most important development relative to enabling economically viable SSP is the emergence of reusable and affordable boosters for ETO transport, beginning with the Falcon 9 reusable launcher of Space Exploration Technologies, Inc. (SpaceX). At present, SpaceX is developing a still lower cost launch option: the Starship and Heavy Booster option, with public statements suggesting that the ETO cost that might be achieved by this system will be below $100–$200 per kilogram to LEO.

Moreover, there are several other reusable launch vehicles under development. They include the New Glenn launcher of Blue Origin, as well as reusable launchers from New Zealand's Rocket, Japan, China (a new version of the Long March 9), and by the European Space Agency (ESA). Altogether, there may be as many as 5–8 reusable launchers operating by the end of the 2020s. This suggests rather strongly that that there will be a very competitive market for SPS launch contracts by 2030.

SPS–ALPHA Ground Segment

As noted above, the ground segment of the SPS–ALPHA concept includes a large rectenna receiver, associated energy storage, and ground control systems.

Ground Receiver

To achieve retrodirective phase control, the ground receiver for SPS–ALPHA will comprise two primary systems: the rectifying antenna (rectenna) and a pilot signal system (RF frequency source and transmitting antenna). The ground receiver for a system using a frequency of 2.45 GHz and delivering approximately 2 GW (with a transmitter of 1,800 meters in diameter) from GEO would be about 6,000 meters in diameter on the equator directly below the platform (i.e., an area of 28 km^2). This size reflects a maximum interception of the arriving microwave transmission of about 96%. However, because it is a Gaussian distribution, intercepting 50% of the microwave transmission would require an area less than one quarter as much.

The required receiver diameter for a given beam interception increases with increasing distance from the point directly below the SPS, with the cosine of the changing angle, so that at the maximum angle the diameter might increase to a maximum of about 8.5 km (an area of 56.5 km^2). This compares very well with typical land areas required for hydroelectric power plants, as illustrated in Figure 3 for 2,000 MW SPS–ALPHA at 27 km^2-to-56.5 km^2, versus the case of the 500 MW (average) Hoover Dam in the United States at 640 km^2 (reservoir area) and 435,000 km^2 (catchment area).[4]

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[4] See en.wikipedia.org/wiki/Hoover_Dam.

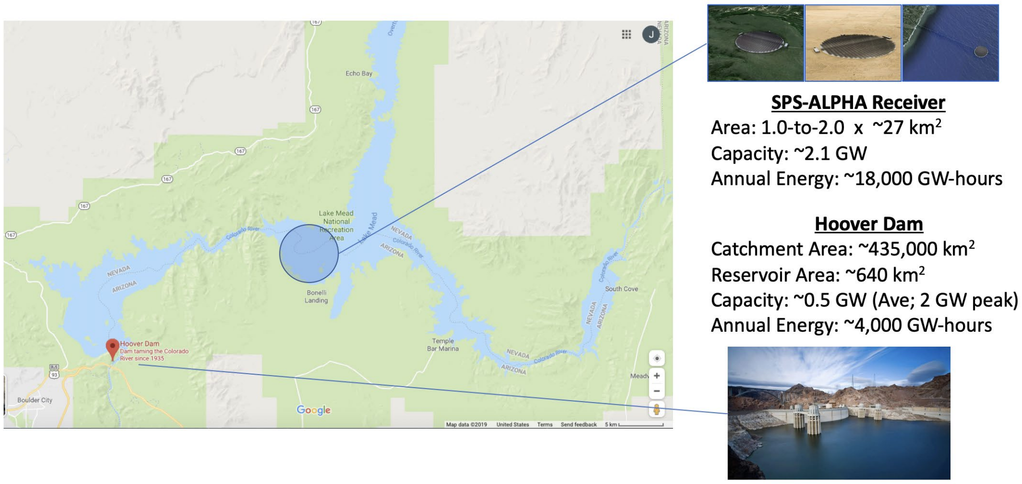

Figure 3. Example Rectenna Area @ 27 km^2 Compared to Area of the Lake Mead Reservoir for the Hoover Dam

Energy Storage

Energy storage is required to achieve nearly continuous power delivery from a GEO-based SPS–ALPHA system due to the periodic shadowing of the platform in March and September (the vernal and autumnal equinoxes). Lasting for about two weeks—the maximum duration of the shadowing is some seventy minutes at the mid-point of the period—which provides a minimum size for the energy storage system.[5] The total energy storage required for continuous power delivery would therefore be about 2.3 x 10^6 kWh.

By sharing the power delivered from a single 2.1 GW SPS among three ground receivers with energy storage at this scale, each might deliver 700 MW of power continuously. Alternatively, one might use the power delivered from an SPS to supplement terrestrial solar power systems.

Ground-Based Mission Control

A third major element of the SPS–ALPHA ground infrastructure is a ground control system, where a single such mission control center might very well be used to operate multiple largely autonomously self-assembling and maintaining solar power satellites. The mission control centers that are now in use for mega-constellations (e.g., Starlink, Kuiper system) may be useful models for this purpose.

Prospects for Low-Cost Deployment

There are three essential elements required for low-cost deployment of SPS systems (space and ground segments). These include very low-cost ETO, affordable and timely

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[5] G. Maral and M. Bousquet, *Satellite Communications Systems: Systems, Techniques and Technology*, 4th ed. (Chichester, UK: John Wiley & Sons, 2004).

transportation from LEO to the desired operational orbit for the SPS (i.e., typically geostationary Earth orbit, GEO) and cost-effective assembly, repair, and maintenance of the SPS platform. As noted above, recent advances in reducing ETO costs through the development of affordable, reusable boosters have dramatically advanced the prospects for cost-effective SSP.

In addition, there have been dramatic advances in the capabilities of various morphologies and markets related to robotics in the past two decades—from robots as simple as household cleaning systems to larger and more capable warehouse robots to a variety of novel body types (and sensor packages) developed for emergency or combat operations. All in all, the prospects for affordable and resilient SSP assembly, repair and reconfiguration have made great strides.

Sustainable Concepts of Operations

A central issue that is often raised *vis-à-vis* the CONOPS for SSP systems is that of disposal at the end of life for the space segment. In the case of traditional GEO satellites (typically communications satellites), disposal of failed platforms is typically handled by reserving a small amount of propellant and using it to boost the soon-to-be-dead spacecraft out of GEO and into a so-called graveyard orbit—where it remains forever. Of course, this solution is problematic going forward: orbital debris has been identified as an increasing concern in LEO, and parking ever-larger numbers of defunct satellites weighing a few tonnes in mass in orbits near GEO can only lead in time to collisions and more debris. How much less acceptable then to suggest taking the same route with an SPS weighing thousands of tonnes?

In the case of highly modular solutions such as SPS–ALPHA, it has been proposed that there would be no singular end-of-life event; rather, the modules of such platforms would fail occasionally—a few each year—to be replaced or repaired. The platform as a whole would continue indefinitely; however, what about the modules that fail each year?

The economic modelling developed for SPS–ALPHA assumes a failure rate of about 3% per year. (As a result, the effective lifetime of the SPS–ALPHA may be viewed as 33 years; however, operational capability represented by the platform will continue indefinitely.) Consequently, for a 7,500,000 kg platform, the annual total dead module disposal would be a mass of about 225 tonnes per year.

An approach that would be sustainable over a long period might be to remove these modules from the operational orbit (GEO) to a permanent graveyard at the Earth–Moon Libration Point L3. This location, which is not being considered for lunar operations (as is EM L1), or for large space habitats (as has been EM L5), is accessible with a relatively modest additional investment of energy at about 1,500 m/s. (Note that this is the same delta-V required for 30 years of station-keeping in GEO at 50 meters-per-second over 30 years.)

Markets and Carbon Net-Zero Goals

The United Nations Intergovernmental Panel on Climate Change COP26 was held in Glasgow, Scotland in the Fall of 2021. This meeting and other studies established as a goal for global industrial civilization that the consumption of fossil fuels must be reduced to a near net-zero level by the middle of the century and that the greenhouse gas emission-driven global warming effects must be held below 1.5°C (about 3°F). Recent announcements (October 2022) from the United Nations suggest that this goal cannot now be achieved; a new objective (i.e., target maximum acceptable temperature increase) has not yet been announced.

Conclusions

A number of critically important changes have occurred during the past several years in the field of SSP in general and SPS–ALPHA in particular. This has framed an integrated view of how these changes impact the technical viability and economic viability of modular SSP systems—in particular the current version of SPS–ALPHA, which was the hyper-modular SSP capable of 24-7 operations published about a decade ago. Although a variety of configurations are possible, this approach to SSP is at the present time the most promising in terms of prospects for both effective and resilient deployment and affordable and cost-effect power generation.

SSP has become a far more serious candidate for a carbon net-zero energy option for global markets during the past handful of years. There are several reasons: the reduction in launch costs due to emerging reusable boosters; advances in key technologies such as robotics, high-efficiency electronics, and others, and the prospects for low-cost space hardware demonstrated by new, affordable mega-constellations. These have been proven to be directly applicable to the affordable and timely development of SSP through novel, hyper-modular concepts such as SPS–ALPHA. A new option for disposal of failed SPS–ALPHA modules has been proposed: the EM L3 point on the far side of the Earth from the Moon.

Ongoing developments (e.g., in the UK, Japan, China, etc.) and prospects for future programs will determine whether and what SSP concepts continue to emerge and evolve.

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About the Author: John C. Mankins is President of Artemis Innovation Management Solutions LLC and of Mankins Space Technology, Inc., and a Director of Solar Space Technologies Ltd. Pty. He is Vice President of the Moon Village Association, and is a Dean and Professor at the on-line Kepler Space Institute.

While at NASA and JPL, Mankins held numerous positions, including in the Office of Space Flight, Assistant Associate Administrator for Advanced Systems (acting), and Chief Technologist for Human Exploration and Development of Space. He received the NASA Exceptional Technology Achievement Medal.

He holds a BS (Harvey Mudd College), an MS (UCLA), and an MBA (Claremont Graduate University). He is a member of the American Association for the Advancement of Science, the IEEE, Sigma Xi, and the International Academy of Astronautics.

Mankins is known for writing the definitions of the Technology Readiness Levels and as the world's leading expert in the field of Space Solar Power.

Editors' Notes: John Mankins has been working toward the promise of Space Solar Power for decades, and he wrote an authoritative book on the subject in 2014.[6] This article is his first contribution to the *Journal of Space Philosophy*, and it's a timely one. With the recent advances he describes, the market for Space Solar Power has been projected at between $300 billion[7] and $1 trillion by the end of the decade.[8] It may be as inexpensive as 20% the cost of fossil fuels by 2040.[9] This source of power has the potential to revolutionize the world's economies in the coming decade, and John Mankins's work is leading the way. ***Mark Wagner and Gordon Arthur*.**

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[6] www.amazon.com/John-Mankins-Space-Solar-Power/dp/B00N4IXV06/.

[7] www.globenewswire.com/en/news-release/2022/09/06/2510112/0/en/Solar-Power-Market-Size-Worth-USD-293-18-Billion-Globally-by-2028-at-6-9-CAGR.html.

[8] www.alliedmarketresearch.com/space-based-solar-power-market-A07358.

[9] www.nextbigfuture.com/2020/12/future-2040-solar-will-be-five-times-cheaper-than-fossil-fuel-electricity.html.