Position Paper:

Clean Energy from Space:

Has Space Solar Power's Time Come?

January 2022

Change that promises vast quantities of clean, nearly carbon-free power is coming. Specifically, Space Solar Power (SSP) is coming. For the purpose of this paper, SSP refers to solar energy gathered in space, beamed to the ground, and converted to electricity. SSP has been studied for decades and found to be technologically feasible but thus far not competitive financially. In the past, projected costs, particularly launch and manufacture, were too high to be commercially viable. However, that situation is changing.

Recent SSP Activity

SSP launch and manufacturing costs are dropping dramatically and driving a new, powerful wave of SSP interest and activity. These include:

1. Japan's Basic Space Law has been modified to include demonstration of SSP microwave wireless power transmission from low Earth orbit (LEO) to Earth by 2025.

2. In September 2021, the UK Department for Business, Energy and Industrial Strategy (BEIS) received a very positive report (Space based solar power: de-risking the pathway to net zero) commissioned from the independent Frazer-Nash Consultancy suggesting that:

    a. SSP is technically feasible.

    b. SSP is environmentally sound and supports Net Zero[1] pathways.

c. SSP is affordable, with a competitive projected Levelized Cost of Electricity[2].

d. SSP can supply baseload[3] power. Baseload power is continuous 24x7 power, as opposed to the intermittent power of ground solar and wind. Combining SSP baseload power with intermittent ground sources is a powerful recipe for a large and resilient power supply.

e. SSP can provide perhaps 15% of UK (United Kingdom) electricity by 2042.

f. Development of SSP would bring substantial economic benefits to the UK.

3. This led to the establishment of the UK based Space Energy Initiative created to develop SSP in conjunction with the international community. An impressive list of well known companies, universities, and governments are members of the initiative.

4. In August 2021 the Innovation Frontier Project, part of the Progressive Policy Institute, published Daniel Oberhaus' Space Solar Power: An Extraterrestrial Energy Resource for the U.S. From the report: "In this paper, we make the case for space-based solar power (SSP) megaprojects as relatively low-cost, scalable, renewable, and always-on power source for on- and off-world applications. Although SSP is a space-based energy asset, it has the potential to rapidly accelerate decarbonization on Earth while also fulfilling space exploration priorities."

5. In August 2021 the Beyond Earth Institute published Catching the Sun: A National Strategy for Space Solar Power, and also published a draft Presidential Policy Directive on the same topic. From the executive summary: "Space Solar Power can fulfill the promise of clean, safe, renewable, affordable energy reliably delivered where and when it is needed. Space Solar Power can power the world, and power worlds beyond, while moving our civilization beyond the fossil fuel age."

6. Caltech recently announced that they have received more than $100M in private donations since 2013 to develop SSP technology. There is a large group of Caltech professors, staff, students and postdocs continuing this work. Space flights to test some of this technology have been flown and more are expected soon.

7. The National Space Society (NSS), which has promoted SSP for decades, has a renewed program specifically aimed at SSP promotion. Past NSS SSP position papers include:

a. A Public/Private COTS-Type Program to Develop Space Solar Power January 2020

b. Space Solar Power: Enabling a Green Future with Economic Growth July 2019

c. How Space Technology Benefits the Earth July 2019

d. Space Solar Power and Feed-In Tariffs Nov 2013

e. Space Solar Power Oct 2007

8. In 2020 the Alliance for Space Development made SSP one of its four legislative objectives starting in 2020 and continuing to the present. The alliance is an organization of 15 nonprofits dedicated to promoting space development and space settlement in Congress and the Administration.

9. The Aerospace Corporation's Center for Space Policy and Strategy produced a paper, Space-Based Solar Power: A Near-Term Investment Decision, noting the progress that has been made recently and suggesting that substantial, sustained SSP investment should be under serious consideration.

10. The IEEE Journal of Radio Frequency Identification is planning a special issue on SSP in September 2022.

11. ESA (European Space Agency) is planning an international workshop entitled Space-Based Solar Power for Net Zero 2050.

12. The Department of Defense is requesting over $67M for fiscal 2022 SSP development. Projects include power beaming and the development of 'sandwich' modules that take in sunlight on one side and emit microwaves on the other[4].

13. The U.S. Air Force's X-37B space plane was launched in May 2020. It carried and tested a sandwich module developed by DoD's Naval Research Laboratory in the PRAM Mission[5].

14. China's increasing space development success combined with their SSP work is raising eyebrows. China reportedly plans to begin their SSP program with a small-scale electricity generation test in 2022, followed by megawatt-level power generation in perhaps 2030[6]. Commercial, gigawatt-level power generation from space is targeted for 2050.

China has proven it can operate in space, with a small space station in orbit now and working hardware on the Moon and Mars. If China or someone else masters SSP well ahead of others they will quickly dominate near-Earth and cis-lunar space with huge satellites built to satisfy Earth's and lunar energy needs. As a result, they will gain enormous soft-power benefits from being able to rapidly deliver electricity to third world countries and disaster areas. If China develops SSP, it will greatly increase their geopolitical power on Earth.

Why so much interest now?

First, because the dominant costs of SSP, launching and manufacturing, are dropping like a stone, bringing economic viability much closer. Second, awareness that we must migrate our massively carbon-based energy systems to technologies that avoid harming the Earth's environment, particularly the atmosphere. SSP is very clean and can potentially supply vast quantities of carbon-free energy.

Orders of Magnitude Cost Reduction

There are two arenas that between them dominate SSP costs: launch and manufacture. As we will see, it is reasonable to expect that in the near future the costs of both will be reduced by about two orders of magnitude compared to the Space Shuttle era.

Launch Cost Reduction

In 2011 the Space Shuttle flew its last flight in the midst of a long era of $20,000 per kg or more launch costs, primarily on expendable boosters. Today (2021), the cheapest launch vehicle is the partially reusable SpaceX Falcon Heavy with an advertised launch price of around $1,400 per kg, a reduction of well over an order of magnitude. But this is just the start of the near term cost reductions.

SpaceX has been developing the fully reusable and very large[7] launch vehicles Starship and Super Heavy. Suborbital flight tests have been successful. These vehicles, due to full reusability, large size and other developments, have an estimated launch cost of somewhere around a few hundred dollars per kg, another order of magnitude reduction. While SpaceX frequently misses deadlines they have consistently achieved their performance goals eventually. They build and operate the most successful launch vehicle of our day, the partially reusable Falcon 9, suggesting that SpaceX knows how to build cost-effective rockets.

This suggests it is reasonable, within a few years, to expect a reduction in launch cost of around two orders of magnitude when compared to the Space Shuttle era, the period within which studies found SSP too expensive due to launch costs. But there is more.

Manufacture Cost Reduction

While launch costs are a major fraction of the economic problem faced by SSP, they are not the largest. Satellites are generally significantly more expensive than their launch. Typical cost of a payload can range from a few thousand to a few hundred thousand dollars per kg[8]. Such high prices reflect that traditional payloads are handcrafted one-of-a-kind systems. One way to significantly reduce costs involves designing and manufacturing large numbers of identical components to amortize production automation and achieve other economies of scale. The problem for SSP, a new source of power, is to get economies of scale when building the first operational powersats[9].

The communication satellite mega-constellations are leading the way to this step. Each mega-constellation consists of hundreds or even thousands of identical, or nearly identical, spacecraft. These spacecraft can be, and are, mass produced. For even a single constellation the number of satellites is large enough that engineers can get economies of scale. For SpaceX's Starlink, that drives cost to about one percent of the cost of traditional communication satellites[10]. This derives from the typical historical cost of a satellite in Earth orbit of approximately $100,000 to $300,000 per kilogram, versus the cost of a Starlink satellite. A Starlink has a mass of about 275 kg and costs about $500,000 per satellite—which works out to less than $2,000 per kilogram. Thus there is a cost reduction of approximately 100-fold. As you may have guessed, there is more.

The SPS-ALPHA (Solar Power Satellite by means of Arbitrarily Large Phased Array)[11] design takes the next step, generating economies of scale in the manufacture of a single, albeit extremely large, satellite. SPS-ALPHA consists of about two million modules[12] of about 16 types, an average of about 125,000 modules per type. This is a sufficient number for economies of scale and learning effects to drop costs. The list of module types changes as the design matures, but for illustrative purposes, a few of these types might be:

1. An adjustable mirror module type that reflects sunlight onto an array of beam generation modules.
2. A beam generator 'sandwich' module type that takes sunlight from one side and emits microwaves for a phased array.
3. A simple robot arm type that can work in groups to construct and repair powersats by adding and removing modules.
4. A module type with electric propulsion for station keeping and transferring the finished powersat from a construction site, likely in low Earth orbit, to operations in geosynchronous orbit where a powersat can stay visible at one point in the sky with only brief eclipses near the equinox.

In addition, there are a number of trusses[13] built using the same simple robots or any of a number of space truss systems under development. Building the trusses is likely to be the first step in powersat construction. Using the trusses for structure, modules will be assembled in a space environment designed for robotic construction and repair. The closest analogy is a robotic warehouse where automated robotic forklifts move pallets. This is a much easier task than, say, navigating on the surface of Mars, which is not designed for robotic exploration.

These reductions in cost should make SSP a viable energy source for commercial reasons alone. But, there is more. SSP is approaching economic availability just as there is a desperate need for carbon-free power.

Protection of Earth's Atmosphere

Earth's atmosphere is, by far, our most valuable asset. We are adding CO_2, CH_4 (carbon dioxide and methane) and other greenhouse gasses to the atmosphere in vast quantities, mostly as a result of energy production. This heats the atmosphere and amounts to a poorly controlled experiment with poorly understood but potentially catastrophic outcomes.

SSP can help reverse this dangerous climate trend by providing very large quantities of energy with minimal emissions of greenhouse gasses. Greenhouse emissions are limited to the launch and ground antenna maintenance. Ground operations are minimal and can employ electric vehicles. Launch greenhouse emissions may be very close to zero depending on the fuel. Many existing and near-term rocket fuels are carbon-based and do, as one might suspect, contribute to SSP's carbon footprint. The most common of carbon based rocket fuel is RP1 but methane is cleaner. A few launch vehicles use hydrogen for fuel and so have close to a zero carbon footprint. Better yet, in the long run all forms of launch pollution can be completely removed from Earth by manufacturing SSP components in space using lunar or asteroidal materials.

Elon Musk has announced his intention to make the methane fueled Starship/SuperHeavy launches net zero by using atmospheric carbon dioxide to manufacture methane, a process he also plans to use on Mars to refuel the Starship for a return to Earth. Additionally, it should be noted that any carbon emissions associated with launch are one-time events, so should be amortized over the lifetime of the SPS being launched.

Baseload Power

New green energy is needed to eliminate global warming without a massive reduction in lifestyle for the fortunate or forcing the poor to stay that way. Wind and ground solar can provide a significant portion of that energy. However, since wind and ground solar are intermittent they must be combined with baseload power or large amounts of energy storage. This is necessary for intermittent renewables to be part of a reliable power system.

SSP is a particularly attractive option for baseload power as it should:

1. Be available roughly 99.5% of the time from a single satellite and more for multiple satellites. Short outages occasionally happen near equinoxes where geosynchronous satellites are shadowed by the Earth.
2. Have completely predictable and short outages that can be briefly replaced by batteries or other stored power at the ground receiving antenna. Alternatively, multiple powersats can share a number of ground receiving antennas switching between them as needed.
3. Be able to switch receiving antennas very quickly as demand changes.

The ability to provide baseload power with only short and predictable outages makes SSP a good partner for the emerging 'green' electrical grid consisting of production by both intermittent and baseload assets.

Conclusion and Recommendations

Mass production of SSP modules combined with fully reusable, very large launchers in flight test today are changing the playing field. The potential of a two orders of magnitude cost reduction in the most expensive parts of a spacecraft, launch and manufacture, means the business case for SSP may at long last be closing. Of critical importance is that SSP can provide vast quantities of clean power to help decarbonize civilization. An important detail is that SSP may provide baseload energy to terrestrial grids at an affordable price, making achievement of Net Zero much easier. At its core, this is why there is so much current interest.

The next step is to convert interest into research, development, and—when ready—deployment of SSP. The NSS position paper A Public/Private COTS-Type Program to Develop Space Solar Power, January 2020, calls for immediate new funding for SSP. Additionally, the National Space Society endorses the Defense Department funded SPS research referred to in the Alliance for Space Development 2021 objectives.

SSP can make for a brighter future; we can and must grasp it!

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[1] Net Zero refers to removing as many emissions as are added so that there is no increase in carbon.

[2] Levelized Cost of Electricity is a measure of the cost of an energy option equal to lifetime cost of the energy source divided by the total amount of energy produced. This is usually used by investors.

[3] Baseload power is the minimum level of demand on an electrical grid over a span of time, such as one week.

[4] NRL PRAM Mission: One Year and Still Going, 10 June 2021

[5] ibid

[6] China's super heavy rocket to construct space-based solar power station Andrew Jones, SpaceNews, June 28, 2021.

[7] Larger launch vehicles tend to have lower cost of launch per unit mass than smaller vehicles.

[8] John Mankins, personal communication, Summer, 2021

[9] A powersat is an SSP satellite.

[10] John Mankins, verbal presentation, Summer 2021.

[11] New Developments in Space Solar Power. John C. Mankins, NSS Space Settlement Journal, December 2017.

[12] "IAA Decadal Assessment of Space Solar Power: A Progress Report" John Mankins, 72nd International Astronautical Congress 2021, IAC 2020 / C3.1.1.

[13] New Developments in Space Solar Power. John C. Mankins, NSS Space Settlement Journal, December 2017.

About the National Space Society (NSS): NSS is an independent non-profit educational membership organization dedicated to the creation of a spacefaring civilization. NSS is widely acknowledged as the preeminent citizen's voice on space, with over 50 chapters in the United States and around the world. The Society publishes *Ad Astra* magazine, an award-winning periodical chronicling the most important developments in space. To learn more, visit space.nss.org.