National Space Society

Position Paper:

A Public/Private COTS-Type Program to Develop Space Solar Power

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Abstract

The National Space Society (NSS) proposes a public/private partnership approach to develop and demonstrate space solar power at a sufficiently high level of technical maturity that commercial energy providers can subsequently build initial operational systems for high-energy-cost environments such as remote locations (islands, mining facilities, military encampments, etc.), emergency settings (e.g., evacuation camps) and others. The outlines of the partnership are based on the successful Commercial Orbital Transportation Services program that helped develop the SpaceX Falcon 9 launcher/Dragon capsule and the Orbital Sciences Corp. Antares launcher and Cygnus spacecraft. The Space Solar Power Demo development described here features minimal NASA oversight, milestone-driven fixed-price pay-outs, minimal exit criteria, substantial commercial partner funding commitments, non-traditional contracts (e.g., Space Act Agreements with NASA), commercial partner choice of energy market and energy consumer, enabling system development (e.g., space robotics), and at least two winners.

Acronyms

AFRL	Air Force Research Laboratory
C3PO	Commercial Crew and Cargo Program Office
CAST	China Academy for Space Technology
COTS	Commercial Orbital Transportation Services
CP	Commercial Partner
GEO	Geosynchronous Earth Orbit
GFE	Government Furnished Equipment
GSA	General Services Administration
ISS	International Space Station
ITU	International Telecommunication Union
JSC	Johnson Space Center
LEO	Low Earth Orbit
NASA	National Aeronautics and Space Administration
SAA	Space Act Agreement
SSP	Space Solar Power
SSPD	Space Solar Power Demo
TRL	Technological Readiness Level

Introduction

For the purpose of this paper, space solar power (SSP) refers to gathering solar energy in space and beaming it to Earth. Once built, space solar power systems can supply enormous amounts of baseload energy without producing carbon emissions or nuclear waste. Unlike wind power and terrestrial solar, expected SSP production levels are predictable and continuous, except for a few hours per year near the spring and fall equinoxes.

SSP physics is well understood and much of the underlying technology has been used operationally or proven in a laboratory environment, i.e. are at TRL 4-5[1] or higher. However, there is still significant system-level engineering uncertainty and financial risk—in large measure because SSP is an as-yet unproven approach to energy. Much of this risk can likely be retired by a sub-scale SSP plant demonstration (SSPD) at TRL 7.[2] Space solar power is not a new idea, but it warrants a fresh look due to the changing technological landscape. SSP faces significant engineering and financial barriers but some of those barriers are now crumbling.

Cost Barriers

Launch costs have been a primary barrier to SSP. Even using advanced technologies the hardware to gather gigawatts of power in space is heavy and, for the near future, must be launched from Earth.[3] However, transportation costs from Earth to LEO (low Earth orbit) have dropped from $18,900/kg (NASA Shuttle) in 2011 to as low as $1,200/kg (SpaceX Falcon Heavy) in 2019, while payload capacity to LEO has increased from 25,000 kg (NASA Space Shuttle) to 63,800 kg (SpaceX Falcon Heavy). Furthermore, a new generation of spacecraft, SpaceX's Starship/Super Heavy and Blue Origin's New Glenn, promise to reduce launch costs still further, perhaps dramatically. Most SSP concepts locate the space segment in GEO (geostationary Earth orbit) so there will be an additional cost to get SSP hardware from LEO to its operational orbit. Using the SPS station-keeping thrusters to also lift the SPS to GEO from LEO would result in a dramatic cost savings.

A second barrier is the cost of producing and deploying SSP space segment hardware. The production cost is addressed by recent concepts [Mankins 2017, Mankins 2014]. Specifically, by building SSP out of very large numbers of a few standard modular components, manufacturing economies of scale can be achieved for much of the system. The recent concepts for very large-scale LEO communications constellations (e.g., Starlink, OneWeb, etc.) depend on exactly the same economies of production—which are now being proven by several firms.

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[1] TRL 4: Component and/or breadboard validation in laboratory environment. TRL 5: Component and/or breadboard validation in relevant environment.

[2] TRL 7: System Adequacy Validated in Space.

[3] In the long term the space segment of SSP can be built with lunar or asteroidal materials, eliminating most of the environmental cost of manufacturing on Earth and launching SSP components through our atmosphere.

Additional savings can be achieved by designing the construction and operation of the space segment as a structured robotic workplace, similar to automated warehouses, where SSP components are designed to be automatically assembled by simple robots teleoperated as needed from Earth. Large numbers of simple robots capable of working together are well within the current state of the art on Earth for some applications.

Strategic Considerations

The energy market is so large that those who develop successful SSP first may quickly find themselves the leading developer of near-Earth space, which would be filled with their enormous energy-gathering satellites. In part for this reason, the U.S., Japan and China all have SSP programs.

The Air Force Research Laboratory (AFRL) in New Mexico has a >$100 million contract with Northrop Grumman to develop hardware for SSP-related experiments. The driving application for this program is to deliver energy to forward operating bases in remote regions. These bases are currently supplied with energy primarily from fuel hauled by trucks which are vulnerable to attack. This results in very high energy costs at forward operating bases. This is the Space Solar Power Incremental Demonstrations and Research Project [AFRL 2019]. In addition, the Operational Energy organization in the U.S. DOD has for several years been pursuing projects to develop power beaming [DOD 2019].

In 2008 Japan passed its Basic Space Law and it includes SSP as a national objective [Japan 2008]. Since then Japan has had a small but important SSP R&D program. In 2015, two Japanese companies demonstrated kilowatt-scale microwave wireless power transmission as part of this ongoing effort.

China is also making significant investments in SSP. The China Academy for Space Technology (CAST) has an SSP program and in 2015 showcased their roadmap at the National Space Society's International Space Development Conference [ISDC 2015]. The Chongqing Collaborative Innovation Research Institute for Civil-Military Integration in China is constructing a facility for SSP testing. Combined with their dominance of ground solar panel production, China is well positioned to become the major power in all forms of solar energy.

Integration with Terrestrial Systems

Space solar power is an ideal complement to the large and growing networks of ground-based solar and wind producers. These networks generally have a variety of intermittent sources that deliver power at different times and may include energy storage, e.g. batteries or pumping water uphill for when none of the power sources are producing. Sizing the storage is non-trivial as any storage system can run out of power given enough cloudy days without wind.

Adding dispatchable SSP can create a networked power system much easier to operate because SSP acts like a battery that never runs dry. Power delivery is predictable, continuous, and SSP satellites can even transfer power to different networks (via ground receiving stations up to 1,000s of miles distant from one another) as grid requirements in various places change over the course of a day. Modern SPS designs allow for easy and inexpensive delivery of power to multiple physically distant ground receiving stations.

Public/Private Partnership

There are many possible approaches to developing SSP. Here we propose a public/private partnership based on NASA's successful Commercial Orbital Transportation Services (COTS) program that developed the Space Exploration Technologies Corp. (SpaceX) Falcon 9 launch vehicle and Dragon capsule, and Orbital Sciences Corp's (now Northrop Grumman) Antares launcher and Cygnus spacecraft. These systems are used today to deliver cargo to and from the International Space Station (ISS). The Johnson Space Center (JSC) Commercial Crew and Cargo Program Office (C3PO) oversaw the COTS partnership [Lindenmoyer 2014]. NOTE: [Lindenmoyer 2014] is the source for most of the information in this section.

The commercial environment for launch vehicles had an important similarity to the current situation with SSP—there was a non-NASA market that could be serviced by successful development. In the case of COTS this sector (launch) was relatively small. In the case of SSP, the commercial market is enormous, measured in trillions of dollars. However, the prototype SSPD systems described in this paper will require significant scaling and improvements before they can be considered operational whereas the COTS program resulted in rockets that were operational immediately after the developmental phase was complete.

The COTS program chose two commercial partners, SpaceX and Rocketplane Kistler Limited Inc. to provide rides for payloads to and from the ISS. Kistler early on missed financial milestones and was replaced by Orbital Sciences Corp. The Kistler financial milestones were frontloaded as the financial risks were known. As a result, most of the money allocated to Kistler was never debited and instead could be redirected to Orbital Sciences' efforts. Only $32 million (of $207 million allocated) of government money was granted to Kistler for reaching milestones. As for SpaceX, they invested $454 million whereas the government contribution was $396 million. Orbital spent about $590 million in internal funds while the government contributed $425 million to that effort. Thus, COTS and SSPD involve similar amounts of money (see below).

NASA oversight was limited to establishing milestones and the criteria for determining completion, as well as evaluating and negotiating bids. C3PO only employed 14 direct and matrixed personnel. Most requirements were established by the commercial partners (CPs), not NASA, and the CPs conducted all design, development and testing. NASA defined the key needs, safety expectations, and ISS proximity operations requirements. CPs had access to NASA-wide expertise on an as-needed basis, which turned out to be vital.

Milestones had a due date, a set of criteria, and a fixed-price award for completing the milestone. All of this was pre-negotiated between the CP and NASA and renegotiated as needed. It should be noted that the milestone award fee was never changed. SpaceX started with 40 milestones and added an additional 18 when extra funding became available. These were incorporated into Space Act Agreements (SAA) rather than traditional procurement to improve contracting speed and flexibility. This gave the parties the ability to quickly negotiate changes to the milestones as needed, which proved to be quite valuable. In one case it was possible to eliminate an entire test flight with acceptable risk.

There were only three reasons NASA could terminate a COTS SAA:

1. Reasons beyond NASA's control such as not receiving appropriations, war, national emergencies, etc.
2. Mutual agreement between NASA and the commercial partner.
3. Commercial partner (CP) failed to meet a milestone.

Once a milestone was missed, NASA was required to determine the cause of the failure and decide if continuation was in the government's best interest.

This minimal set of exit criteria made planning more consistent and predictable.

Lessons Learned

The lessons learned on the COTS program were (quoted from [NASA 1]):

> Government seed money was highly leveraged
>
> • Commercial partners funded over 50% of COTS development costs
>
> Fixed price milestone payments maximized incentive to control cost and minimize schedule delays
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> Minimum firm requirements along with commensurate Government oversight were key to fostering innovation and reducing life cycle development costs
>
> • Goals (vs. requirements) were established to open trade space and optimize design
>
> • Firm requirements were identified only where necessary to assure the safety of the ISS and crew
>
> • ISS interface requirements evolved over time and were coordinated in a collaborative manner with the commercial partners
>
> A portfolio of multiple partners with different capabilities assured a balanced approach to technical and business risks
>
> • Increased the chances of at least one successful partner
>
> • Market forces kept development and operational costs in check
>
> Commercial friendly intellectual property/data rights and limited termination liability encouraged investment of private capital

NASA commitment to purchase operational services greatly improves the ability for companies to raise funds NASA does not have the statutory authority to provide Government Furnished Equipment (GFE) under a SAA (Space Act Agreement) • Even though originally contemplated in the SAA and in the best interest of the Government, COTS had to revert to loan agreements and cumbersome GSA excess procedures to transfer equipment to facilitate berthing with the ISS Augmentation of funding late in the program enabled additional risk reduction testing not initially affordable • Directly contributed to the successful first attempt berthing of SpaceX Dragon to ISS • Would be difficult to predict how much, if any, to hold in reserve during program formulation and initialization to protect for such milestone adjustments COTS model for public-private partnerships worked!

The COTS program, which was to develop launch vehicles, was followed by the CRS (Commercial Resupply Services) program which procured these same vehicles for missions to deliver and retrieve cargo to and from the ISS. This provided an early anchor customer that provided sufficient resources for both SpaceX and Orbital to continue to invest in their launch systems and, in SpaceX's case, become a dominant provider of launch services worldwide.

Proposal

We now propose a particular form for the SSPD public/private partnership based on the very successful COTS program used to develop launchers. Unlike COTS, however, this project might benefit by expanded Government representation including the involvement of the Departments of Energy, Commerce, and Defense. The Department of Energy has an obvious interest, the Department of Commerce can help with the user community, and the Department of Defense has a significant SSP effort under way and could also benefit from being an initial anchor customer. Access to the knowledge and experience base of these organizations can be of great value. NASA, however, has a great deal of the expertise necessary for a successful demonstration and there is every reason to believe that, just as with COTS, access to the knowledge and experience of the NASA work force would be extremely valuable.

Here is a short summary of the proposal content followed by additional detail and a discussion of the reasons for various decisions:

1. Final product is a TRL 7 systems-level demonstration of solar energy collected in space and delivered to the ground in useful form.
    a. Need not be profitable or full scale.

2. At least two commercial partners (CPs).
3. Payment is fixed price and milestone driven.
4. Is expected to require $400 million government money over five years.
5. Each CP proposal must
    a. Require significant CP funds.
    b. Include at least one high cost power consumer as a customer.
    c. Deliver usable power from orbit to Earth for at least one year.
    d. Propose a realistic path to gaining any necessary frequency allocation.

1. Final product is a TRL 7 systems-level demonstration

The purpose of SSPD is to increase the technical readiness of the components, systems, and supporting systems of an SSP system to at least TRL 7, including the space segment. This should put industry in a position to start selling SSP plants. This demonstration must be complete, system wide, and include critical supporting technologies (for example, robotic assembly in space). If successful, SSPD should lead directly to full-scale construction and operation of SSP systems for high-energy-cost environments.
The SSPD deliverable need not be profitable or full scale. We are seeking the development and operation of a prototype, not an operational system. Attempting a fully operational, commercially viable system is likely too big of a step currently.

2. At least two commercial partners

The COTS program had two successful CPs to insure competition. In the case of SSPD it is important that each of the finalists use a somewhat different approach: development of two different architectures is more likely to succeed than two efforts doing about the same thing.

As we described earlier, in the COTS program one of the winning CPs (Rocketplane Kistler) missed financial milestones and was cut from the program. In a separate round of competition Kistler was replaced by one of the CPs (Orbital Sciences Corp) that was not chosen in the original competition. SSPD should take a similar approach should one or more of the CPs fail to achieve milestones to the point of being cut. Depending on the amount of government money already expended it may be necessary to renegotiate the previous bidders' milestones and their criteria to compensate for less government funding being available.

3. Payment is fixed price and milestone driven

CP proposals will include
1. List of milestones unique to this CP.
2. Criteria for achieving each milestone.
3. The fixed payment for meeting the criteria.

Milestones may be technical or financial.
Technical milestones might include
1. Ground demonstration of power beaming.
2. Setting up component production factories.
3. Setting up the robotic workplace.
4. Robotic simulator completed.

5. Ground systems deployed.
6. First power delivered to the ground.
7. Etc.

Financial milestones might include

1. Venture capital raised.
2. Loan completion.
3. Etc.

Note that transfers of CP internal funds were not considered a milestone in COTS. This approach ensures that the government will only pay for progress.

4. Is expected to require $400 million government money over five years

[Jaffe 2016] suggested that roughly $350 million would be required to complete SSPD using traditional procurements. We expect that between investing their own money and the kind of efficiencies that were realized in the COTS program an average of $200 million of government money should be sufficient for each of two CPs. This number should be expected to change as greater insight is gained. Note also that the COTS program received $500 million up front and an additional late funding of $288 million that was used for additional testing milestones and this is believed to have played an important role in the success of COTS.

5a. Require significant CP funds

Each CP proposal must have an estimate of the company funds required, and judgement will include an assessment of the amount of private funds that will be devoted to SSPD. In general, it may be necessary for the CP to cover between one-third and two-thrids of total cost to make sure CPs really have “skin in the game.”

5b. Include at least one high cost power consumer as a customer

For the COTS program, NASA was the anchor customer as NASA needed cargo transportation from Earth to the ISS. For the SSPD program there is no obvious NASA anchor customer for the energy produced. Therefore, each CP team must include at least one power customer who commits to receiving and using the power delivered to Earth by SSPD. Ideally this customer would currently pay a very high cost for power, as is the case for remote mining operations where energy cost for trucked in diesel can be as much as $1/kwh or more. The U.S. Department of Defense is an obvious potential anchor customer. Additional potential customers include power utilities in isolated locations such as remote islands and refugee camps.

5c. Deliver usable power from orbit to Earth for at least one year

This requirement is intended to make sure that the systems developed have a high chance of working when scaled to full operation. The amount of power does not have to be large and delivery does not have to be 24/7.

5d. Propose a realistic path to gaining any necessary frequency allocation

For SSP to succeed it must avoid interfering with spectrum users near receiving antennas. Frequency allocation is done by the ITU (International Telecommunication Union) and is an international decision. Thus, it may be wise to include foreign collaborators in CP proposals to broaden the base of countries with a need for SSP frequency allocation and who will support such an allocation. For example, it might be a good idea to include Canada not only for their space robotics experience but also for support at the World Radio Communication conference. However, the benefits of foreign involvement will need to be weighed against the costs of complying with any applicable national security (e.g. ITAR) and export control regulations.
The frequencies chosen must not only be adequate for this demo but have the potential to expand if SSP is successful and takes off around the world.

Additional Observation

Bringing cis-lunar space and the Moon more fully into Earth's economy will require diverse new commercial services. The approach proposed here for space solar power would be a powerful tool in the development and commercial application of a range of other needed space infrastructures. These include, but are not limited to essential capabilities such as space logistics vehicles to efficiently move mass from LEO to other desired orbits (and eventually a lunar gateway or Earth-Moon Libration point to Earth orbit); fuel depots to refuel such logistics vehicles (and satellites and spaceships); and in-space robotic assembly, operations, maintenance, and manufacturing in a competitive and sustainable manner.

Summary

Successful public/private partnerships have a long history going back at least to the first Transcontinental Railroad that stitched the nation together and the Contract Mail Act that helped create modern aviation. In the space domain the COTS program stands out as one of the most successful such partnerships. Given that both space launch and electrical power have a significant non-government market it makes sense to model a partnership for SSP development on COTS, with changes as needed.

SSPD could make a significant dent in the substantial technical risk of SSP development. Yes the potential pitfalls are many, expenses are high and it can take a long time to get a significant return; but the rewards are potentially very great: clean, bountiful, predictable power for as long as the sun shines, without the spectre of nuclear waste or proliferation. Even an unsuccessful program is likely to create a rich harvest of technology development, personnel development, and in-space infrastructure.

Now is the time to be bold.

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