The Space Power Grid to Space Solar Power

Question and Answer Session

If I understood you correctly, SPG in its initial phase would beam power from terrestrial solar plants into space, and then across the world to meet demand elsewhere. Since one of the benefits of solar power is that their output vs time of day very closely tracks the peak power demand vs time of day, what makes you think that terrestrial solar plants would want to sell you their power during the 'afternoon sun'?

It is true that solar plants generate power in the afternoon that tracks demand in cities, so you may be quite right in that they may not have a large amount of power to sell in the afternoons. But if you notice the power level of our Phase 1 satellites, it is only around 60MW each maximum. A typical utility-scale solar plant will have considerably more than twice that, so the correct answer here may be that some plants will only participate in SPG as a marginal side business, if they already have their business plans working well with customer demand tuned to their output. But they still cannot produce any power at night without burning auxiliary fuel, so they will want the system to buy power at night (and on rainy days, if we can figure out the aerostat or other delivery system to tunnel through the weather). And the best way to pay for that may well be to put up more solar capacity at their own plant. The new capacity does not need new transmission lines, so you trade off the lower efficiency of beamed transfer against the savings in capital and finance cost of adding transmission lines. If you are in the middle of, say, the Saharan desert or Arizona or South Dakota, or even Greenland or Antarctica (where the sun does shine on Summer Day, you know...), this may be a winning trade. Point is that the customer base for SPG is everywhere on Earth, not just where people crowd to live now because of grid constraints. You'll have the market to yourself for a decade or so, which is all you need to pay off your installation cost and start rolling in money. :)

Interesting study prospect, but I think the answer will be a positive one.

While we are talking about pie-in-the-sky ideas, what are your thoughts of using a space elevator to transport the necessary equipment into space? How much would the (relatively) cheap cost of getting the equipment into orbit change the economics of the proposition?

A full-scale tether ascent system to Space is even more fanciful than a govt-funded 1GW SSP demo at 2.45 or 5.8 GHz. (concepts only an aerospace engineer would love, so to speak, and that only until they think about it).

For one thing, a geostationary tether requires a counter-mass on the other end, and the concept studies that I have seen in the NIAC studies of the early 2000s before they formed Tethers Unlimited and I lost interest in this, were suggesting 118,000 kilometer long tethers with large masses at the other end. Of course, made of "carbon nanotubes". How those large masses were to reach 118,000 km above Earth is also a good question, there was some answer about them sliding up the tether using solar-powered motors, or beamed laser energy from the ground (check into a company that recently won a NASA Power Beaming contest using a ground based laser).

So far they have identified one region, off the Pacific coast of central / South America, where data show a very low probability of high winds or lightning. I think the Sea Launch enterprise also tried parking in that region, but for other reasons, has not been a success.

Let's let them articulate the actual cost of lifting very substantial masses.

But tethers in fact do offer a very interesting way to reduce launch costs. Think of the X-Prize winners, SpaceShip One. They "reached Space" using runway-launched airbreathing vehicles but only reaching Mach numbers as much as 2 or so, and going up and falling down. The energy level reached was only about 10% of that needed for Low Earth Orbit, so they were very very far from becoming an orbital launch capability.

However, imagine a tether constantly swinging through Space, that comes down close to the Earth, and manages to have a low velocity relative to Earth at the closes approach. In other words, where the SpaceShip One vehicle could latch on to the tether, and the tether would swing it far up into high orbits. The tether would certainly need propulsion of some sort to make up for the momentum transfer, but this may come from a Space-based solar-powered electric propulsion system with very high specific impulse, rather than a massive chemical rocket. The tether would never swing through the atmosphere, so drag and heating are not issues.

This may be the start of a very viable air-breathing reusable vehicle system to deliver payloads of all types with great regularity. I haven't seen any studies of this, but there are studies of delivery to the lunar surface using tethers, so the notion of setting up a tether to match the surface speed at the bottom, is well-developed. Neat Dynamics problem.

Close to Earth's surface, the military has developed techniques to deliver Special Forces equipment to hostile areas where they cannot land or use parachutes (too visible for too long). A C-130 might come flying along, with a jeep or HUMVEE etc swinging below on a tether. The C-130 then executes some maneuver, where the tether swings, and as the load reaches the surface, the relative velocity becomes low enough to just touch down (and unhook real smartly!) I think this was shown in some James Bond movie as well, but it is a real concept. Takes very very precise flying, and the absence of wind gusts.

Tether dynamics is a very interesting field. Check out the name Jerome Pearson or his company, STAR Technologies Inc. for papers and current work. They are now trying to get NASA or DARPA to launch their craft to use tethers to catch junk in Space and either pick it up or directly send it into trajectories that make them burn up.

What customer has a demand curve that fits the "Space Power Grid's supply, which you note provides just 80 minutes of availability per location per day, assuming it isn't raining? Wouldn't sunsats at GEO with 99% availability (capacity factor) be superior to any other power source (nuclear plant capacity factor is only 90%.)

The 80 minute example is at the first startup of the system, using a handful (6?) satellites used in that "afternoon sun" demonstration. A customer who needs to recharge storage in the depths of the night, using excess generation from a hot summer's day provider on the other side of the world, would be a good example of a customer pair who could benefit from this stage. At startup we are clearly talking about interested participants (Charter Subscribers), who are participating in system startup and development. Probably it is their money that we are investing for the development. Example would be the India-US collaboration. The only purpose of that (other than that it took so little time to do the simulation for the students) is that there is no need to be fixated on providing continuous, uniform distribution at the start of the system.

The real comparison there would be with a satellite sequencing that insists on 24-hour coverage, which would mean higher orbits and hence larger antennae, just to prove that you could provide continuous coverage. The better system startup strategy is to put the satellites in tandem as our "afternoon sun" scenario projects, and get a much shorter (but still useful) hour or so, using the low orbits and smaller antennae of the final system.

Once past this demonstration stage, the number of satellites and participant stations would grow, to the 100 and 250 that I have given for breakeven calculation, or to something much larger in number, so I don't see where the concern about "80 minutes" comes from. Once beyond about 36 satellites, I think we would be able to provide 24-hour coverage.

Also, there is any number of permutations and combinations for orbits and types of satellites, and ground stations. Enough to keep Multidisciplinary Design Optimization types busy for a long time, to come up with the "best" distribution.

Consider this: to get up to, say, 4 TW, one needs at least 4000 (four thousand!) 1-GW satellites. That is a much larger number than anything that we have discussed for the grid. Would you really want 1GW beams, or would you want to distribute that among 10 beams? So the issue of providing continuous coverage is not a big issue at all, beyond the first days of startup.

Now to the rain issue. Yes, local rain is a killer (we will go to aerostats or burn-through to get around that). But if it is a thunderstorm in an area served by a terrestrial grid, one can easily find alternative sites within a few miles. If is a Monsoon or a major snowstorm covering a large part of a continent, we would have to hope that our waveguide aerostat solution will hold up. Or, much more likely, we would pay the price to burn holes through the cloud and rain. What happens when you beam CONTINUOUSLY at 60MW through rain or snow? One may lose the first minute of beaming, but I think the beam will win after that.

GEO-based systems, on the other hand, require receiver sites so large that there is no prospect of finding an alternative site within a few thousand miles. So if is raining hard enough, the system is useless. I would like to see data on 2.45 or 5.8 GHz beaming efficiency through heavy rain such as a thunderstorm, or a blizzard. In my experience, dish TV goes out during the Indian Monsoon a lot (a disaster during cricket matches!) Indian Railways microwave data (I have cited in papers) shows signal dropout in fog or coastal areas where there is a lot of spray. The Hawaii experiments conducted by Mankins et al some time back, and the Japanese experiments in Hawaii more recently (shown at Huntsville) both showed reception numbers that seemed much lower than what the diffraction-limited reception should have been (I mean, after accounting for the fact that the antennae were too small to capture even the primary lobe). So I remain quite skeptical about the performance of any of these frequencies whether above or below 10 GHz, in moist, low-lying regions. The difference is that with the GEO-based systems you are stuck, because the receivers are too large to put at every power plant.

You state that the rectenna diameter for GEO SSP systems is about 100 kilometers. Why does Prof. Shinohara, who chairs the Japanese' Microwave Power Transfer(MPT) committee, state that their rectenna diameter will be 2.45 kilometers (for their JAXA2 design, using 5.8 Ghz).
[http://www.sspi.gatech.edu/wptshinohara.pdf:](http://www.sspi.gatech.edu/wptshinohara.pdf)

Table 1.1 Typical parameters of the transmitting antenna of the SPS [7]

Model	Old JAXA model	JAXA1 model	JAXA2 Model	NASA/DOE model
Frequency	5.8 GHz	5.8 GHz	5.8 GHz	2.45 GHz
Diameter of transmitting antenna	2.6 kmϕ	1 kmϕ	1.93 kmϕ	1 kmϕ
Amplitude taper	10 dB Gaussian	10 dB Gaussian	10 dB Gaussian	10 dB Gaussian
Output power (beamed to earth)	1.3 GW	1.3 GW	1.3 GW	6.72 GW
Maximum power density at center	63 mW/ cm^2	420 mW/cm^2	114 mW/cm^2	2.2 W/ cm^2
Minimum power density at edge	6.3 mW/ cm^2	42 mW/ cm^2	11.4 mW/cm^2	0.22 W/ cm^2
Antenna spacing	0.75 λ	0.75 λ	0.75 λ	0.75 λ
Power per one antenna (Number of elements)	Max. 0.95 W (3.54 billion)	Max. 6.1W (540 million)	Max. 1.7 W (1,950 million)	Max. 185 W (97 million)
Rectenna Diameter	2.0 kmϕ	3.4 kmϕ	2.45 kmϕ	1 kmϕ
Maximum Power Density	180 mW/cm^2	26 mW/cm^2	100 mW/cm2	23 mW/cm^2
Collection Efficiency	96.5 %	86 %	87 %	89 %

JAXA : Japan Aerospace Exploration Agency, NASA : National Aeronautics and Space Administration, DOE : U.S. Department Of Energy

$$\frac{D_t\, D_r}{\lambda\, x} = 2.44$$

where

D_t = diameter of transmitting antenna

D_r = diameter of receiving antenna

λ = wavelength of beam

x = distance between antennas (determined by orbit)

Note : parameters must be in the same units ; e.g., all in meters.

The answers can be checked quite simply by putting numbers in the equation above. I assume that the wavelength is given by the speed of light (3 times 10^8 m/s) divided by the frequency in cycles per second (2.45 or 5.8 times 10^9). JAXA 1 actually has 2.79 instead of 2.44 on the right hand side, because it is for 96.5 percent capture of the beam (first side lobe as well as the central main lobe) . JAXA 2 is similar to what I used (2.44 on the right hand side, giving roughly 87% beam capture). I have noooo idea how the NASA/DOE model gives 1km diameter on both the transmitter side and the receiver side, 2.45 GHz and still claims 89% capture, but would be very curious to find out more about the expression that they used for that prediction. I suspect that we are missing something there? If that were possible, why does JAXA bother going to 5.8 GHz? Is a zero missing from the diameter on one side in the NASA/DOE model? I have to wonder (sorry!) whether this is the same Study that promised $100/lb launch cost to LEO using the Space Shuttle.

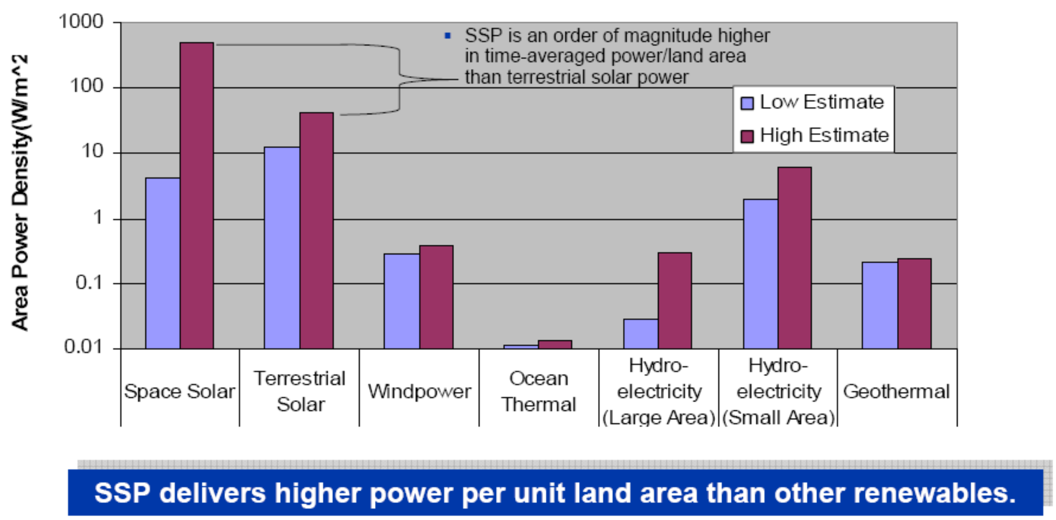
I assume a 100m diameter transmitter in my slide because of the following reasoning. If you want to make the ground receiver smaller, you make the space transmitter larger. Would you REALLY do that, given the cost of launch and deployment? You may, when the system is fully built up in orbit, IF it ever reaches that. But until you do that, you are stuck with the receiver that you have, which is going to be completely inadequate to capture the transmitted beam. This is the key point to note: the percentage spilled over by an inadequate receiver, is independent of the power level.

In other words, if you decide on a 2km diameter ground receiver, then UNTIL your transmitter GROWS and becomes 2.x km diameter, you will lose a much larger portion of your beam simply due to spillage because the beam is so wide. In other words, you will be lighting up or cooking the neighbors with the spillage as you built up the space portion. Saying that you will become a better neighbor when your system gets fully built and the beam gets smaller in 10 years, is not going to make the neighbors happy, is it? How long and how many launches does it take to build up a 2km diameter space transmitter?

So those kilometer-sized transmitters with 2km receivers, are completely impractical and just show that the proposers have not put serious thought into what they are proposing. This is what drove me to put in those cracks about the Mouse on The Moon, and Pie in the Sky. Can they be serious if they propose 2km diameter islands in the sky BEFORE first revenue generation?

Or maybe they always intended for the receiver to be in the middle of the ocean, so that they can have any size receiver that they want and only the fish would complain. (I wonder how successful have tidal or wave energy or offshore wind turbine projects been in laying the transmission high-capacity lines from their offshore projects?).

Launch costs are dominated by the frequency of launch, as the DOE/NASA reference study pointed out which modeled vehicles reused between 50 and 300 times. Wouldn't SpaceX's planned reusable launch vehicle approach provide lower costs than "heavy lift vehicles such as the Ariane vehicle, for example, that you mention? (Existing launch vehicles, such as the Ariane, Delta IV and Atlas are destroyed after one flight. SpaceX plans to make the Falcon 9 first stage reuseable at flight five)



from [Space Solar Power Alternatives - Seth Potter, Boeing Principle Engineer]

I am all for RLVs, and would LOVE to work on those. But I do not see rocket-based, vertically-launched RLVs bringing the launch cost down to the levels used in any of these SSP models. The NASA STS also succeeded in flying 131 missions using 5? vehicles, counting the replacements as the same vehicle as the ones they replaced. This is an average of 26 missions per vehicle, which is certainly not trivial. The launch cost did not come down from the $29,000 per kg to LEO level. One can cite many reasons for that, but that is the demonstrated reality to-date. (Rather you than me to argue otherwise to the news media and Congress). Other RLV efforts such the Russian Buran, the US X-33 / VentureStar etc. did not really take off, so we cannot cite data from those. I certainly hope that we can convince someone that there IS a sufficient market to justify a runway-launched, runway landing, airbreathing RLV that captures its oxygen on the way up, and that this can be at a Shuttle-type payload capacity. But in my latest discussion on that (with our Prof. Alan Wilhite, who has analyzed these things) I came away with two messages. First that there is no market to justify an airbreathing RLV, and second, that the aereal density (mass per unit area) of SSP platforms is too low (mostly thin flat panels) to make efficient packing into something that has to counter atmospheric drag a lot. The first is a chicken-egg problem (we have to convince someone that there IS a market, i.e., full-scale, TW-level SSP requiring tens of thousands of launches paid by private enterprise). The second takes more thought, I have no immediate answer.

Will SpaceX provide much lower costs? Some NASA experts say, "let's see what happens when they encounter their first failures". They already have. The cost that they project for the Falcon 9 (per news reports that I cited) is certainly not low, though it is lower than the STS cost. I suspect that they have no reason to reduce it below what NASA has to pay the Soyuz people. I wouldn't in their place, why would I? :)

Once we are beyond the glut in small launchers due to the dismantling of the Strategic Missile fleets, I do not see why a large launcher will be more expensive per unit payload mass than a small launcher, assuming that we never fly without a full payload. Modern launchers seem willing to put big volume containers (bigger diameter than the rocket) on their rockets, so the issue is how much mass one can lift. The bigger ones should be cheaper. Hence my choice of the Ariane 5 ECA example, which has flown 32 times, so they are well up on the learning curve. US launchers use propulsion systems with lower Isp, apparently, because those engines are cheaper. If you mass-produce, I suppose one can get the H2-LOX engines to be as cheap, so again the Ariane is a better choice for what is possible. Wish I could have used the Boeing/Energia Sea Launch as an example of commercial heavy-lift, but I don't think they exist anymore.

You note that baseload power plants provide premium pricing because they are continuously available. Actually baseload power is the lowest cost because it is used for about 60% of all the power generated. Wouldn't it be a more financially successful strategy to pursue the bulk power market, which is where most of the money is? Doesn't this also fit the 99% capacity factor for SSP at GEO best? (The most expensive is peak power, such as gas turbines, because they have very high maintenance costs because they are rarely used, as intended - mainly during summer emergency less than 1% of the time.)

Ah! Now I am on quicksand, I am answering a question from an industry insider!!! Pardon my ignorance. The issue as I see it is to enable solar (and wind) plants to become RELIABLE baseload providers (I got the definition from an IEEE Spectrum article on wind energy plants one Saturday evening over pizza and Diet Coke) and command prices that only established, reliable preferred providers can command. Perhaps the term "baseload" has nothing to do with the terms "reliable" and "preferred" which may be the real determinant of the price a plant can command. My understanding of the issue cited in Spectrum is that it costs more for the Grid Czars to have a shaky provider whose output fluctuates a lot, so they don't command high prices from the Grid Czars, whereas the Preferred Baseload Provider is the solid citizen who guarantees 95% reliability and the ability to provide surges in supply when the shaky ones drop out and there is a spike in demand. This is not inconsistent with the observation that 60 percent of power on the grid comes from baseload providers. I can see why one would not want the alternative, that is, 60 percent of power on the grid coming from flaky producers who might drop out at any instant.

I don't know what is the "bulk power market", would appreciate knowing so we can see where to use that.

GEO might, yes, provide 99% availability and capacity factor if the rain/snow issue mentioned before is shown to be non-existent. So would a fully populated Space Power Grid, with much more redundancy and flexibility than GEO because you can get help from other satellites and other ground stations. But GEO stations being so large, have the obvious issue that one cannot afford to build and retain auxiliary backup. If an errant supertanker runs into that 100GW line coming from the offshore antenna, or if Cat 5 Hurricane Henrietta or Typhoon Tanya or Tsunami Tsue is passing that way, well... enough said.