Earth *vs* Space for Solar Energy, Round Two

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Can renewable solar energy for terrestrial use be collected more efficiently and cleanly in space than on Earth[1]? Steve Fetter argues[2] that five unlikely conditions would need to be met before space could ever compete economically with Earth in use of solar photovoltaics (PV). Economic competitiveness is a relevant question, and I appreciate the challenge posed by Fetter's arguments; in contrast the variety of contributions on fuel cells and nuclear power listed at the Forum on Physics and Society's web site [3], generally ignore serious economic discussion. Fetter would seem to agree that there are no physical obstacles to space solar power (SSP) deployment, only economic ones.

Economic cost is in fact a major issue for every proposed non-fossil energy source; with nuclear fission, for example, just capital costs to address world non-fossil energy needs of 3-5 TW (electric) by mid-century would amount to 5-15 trillion dollars[4]. Even the lowest projections of capital costs for wind or terrestrial solar power (TSP) see a need for at least ten trillion dollars in spending, if they are the primary solution; those estimates depend on order of magnitude or more improvements in the cost or performance of PV, energy storage, and transmission system components.[4] Probably every physicist would love to see superconducting cables form a mainstay of world energy transmission capacity, but in reality they are still at least an order of magnitude away from being cost competitive with traditional transmission lines.

But these economic and performance issues in most fields are seen as challenges stimulating research and development, in PV materials and electric power transmission and storage technologies for example. Governments also regularly issue technology incentives promoting alternatives believed beneficial to the public good, including providing training and information, promoting standards, building infrastructure and demonstration projects, and very often tax credits and subsidies for the favored technology (or additional taxation on the disfavored, as in proposed carbon taxes and high European gasoline taxes)[4]. Most of Fetter's conditions for SSP to be economically competitive actually translate to research challenges on PV, wireless power transmission, lightweight space structures, and cost effective space launch, for which government demonstration projects and infrastructure development could be key to bringing down costs and increasing capabilities. The challenges are considerably more achievable than Fetter's list would indicate. Fetter claims the comparison argues against SSP research, but a similar analysis for fusion, based on current estimates for ITER and NIF, would find an even worse situation, with costs 10 to 20 times more than could possibly be commercially competitive over the next few decades[5]. Should fusion energy research cease?

Fetter's first condition, that solar supply 100% of electric demand, is the least sensible; demand for electricity varies by region and time, so there is no single market for electric power either at the consumer or production level. In fact generation is traditionally divided into three distinct markets: base, intermediate, and peaking power[6]. The base market reflects the underlying need for round-the-clock electricity and accounts for over 70% of electric power produced in the US. High efficiency, high capacity factors, and low fuel cost are the economic drivers, and coal and nuclear plants (even with their rather high capital costs) are the primary suppliers in the base power market. In contrast, for the peaking power market the drivers are a capability for on-demand start-up and low capital cost, since that capital has to earn returns through sales of many fewer kW-hours of production year round. Oil-fired plants and gas turbines dominate in the peaking supply markets, despite their higher fuel costs.

These distinct markets for power generation and sunk capital costs of existing plants mean competitive technologies will always see gradual introduction, in whichever markets they are competitive (including effective government technology incentives). In particular, SSP meets well the high capacity-factor round-the-clock nature of the base power market, and so is perfectly positioned to displace coal-fired electric plants, the worst of our current CO_2 emitters. In contrast, TSP has high capital cost, low capacity factor, intermittency, and location dependence, which doesn't match well any existing power market's requirements. The coincidence between TSP availability and peak demand means TSP can, at least in some regional markets, address some of the peak capacity needs. But the high capital cost and "when available" rather than "on demand" character actually put it closer to the intermittent/intermediate power market typically filled by renewable options such as hydroelectric and wind.

Energy storage systems can move power demand between the primary time-domain markets (for example pumped hydro at night to supply peaking power during the day) just as the transmission grid can move power from one regional market to another; storage and transmission have their own capital costs, however, as well as losses that reduce final power availability. These costs are sufficient with current technology that the divisions between the distinct power markets are reasonably sharp.

So Fetter's claim that competition will happen only in some sort of aggregate way, and needs to involve complete replacement in one market ("solar provides over 20% of power", capturing the peaking market) before it can start on another, makes little sense under current and reasonably projected electric market conditions. When TSP becomes competitive in the peaking/intermediate power market in the desert southwest region of the US, say, it will grow within that market meeting the need for new and replacement generators. At the same time, if SSP is competitive for base power (and it could compete in every regional market, since SSP receivers could be located within a few hundred km of any major power user) it can grow in that market, independent of what is happening with TSP. A long-term energy future with base power provided by SSP, summer daytime peak power supplied by TSP, and transportation fuels (for non-electric vehicles) supplied by biomass is a reasonable long-term possibility. In reality a mix of all these energy sources will be around for a long time to come.

This also has immediate consequences for the numbers in most of the rest of Fetter's analysis. Making the comparison only for the primary base power market, the factor of $(1 - f(1 - \epsilon'))$ everywhere becomes simply ϵ', the overall efficiency for storage and transmission of terrestrial solar to those regions that need it (assuming production in cloudless desert regions; ϵ' can also serve as a proxy for lower solar flux for TSP systems closer to end users). Fetter's ρ becomes ϵ/ϵ', and for the assumed $\epsilon = \epsilon' = 0.4$ condition, $\rho = 1$, or roughly double what Fetter assumes. This adds roughly a factor of two more leeway for SSP in all the subequent conditions.

Regarding the factor χ, representing the relative capital cost of the PV modules: as Fetter notes, right now commercially available space power modules run several hundred times the cost of terrestrial solar modules, due to their low volume production. Crystalline silicon is the most widely used PV material in both markets, so mass production of space modules should not cost significantly more than for terrestrial modules. Additional component costs (weather-resistant coverings and structural components for terrestrial cells, light-weight structural materials and components associated with launch packaging and orbital unpacking for space cells) could make a cost difference, but in the end χ should be much closer to 1 than the current several hundred, with sufficient R&D effort and market scale. In any case, rather than Fetter's second condition that χ be less than 1, in reality χ can be as high as 3 or 4 and still be competitive for base power, given the corrections to ρ mentioned earlier. This certainly seems achievable.

Fetter's assumption that "in order to be economically competitive [...] C'_{PV} must fall below \$1000/kW$_\mathrm{p}$" hides another interesting issue: currently solar PV modules cost \$2500 to \$3000 per peak kW. If C'_{PV} instead stays at around \$2500 and with $\rho = 1$, the constraint on launch costs becomes only $C_L M < \$10,000$. Beating that requires only $M < 5$ kg/kW$_\mathrm{p}$ and $C_L < \$2,000$/kg, both conditions that are very close to being met with current (underfunded) space technology. But neither TSP nor SSP can practically compete with other options at those prices. Even at the \$1,000/kW$_\mathrm{p}$ level, TSP still is well on the high end with likely costs per base-power kW of \$10,000. In any scenario where the cost of PV components dominates total costs, SSP sustains a 3 to 5-fold advantage over TSP due to the smaller quantities needed, per average kW. The point here is that the higher the basic PV costs are, the more favorably SSP competes with TSP. Solar PV prices have been close to flat since the mid 1990's; in fact average module prices in the US were up 9% in 2002 from 2001, at \$3740/kW$_\mathrm{p}$ [7].

Another significant omission in Fetter's discussion is the widely differing physical characteristics, and therefore likely costs, associated with terrestrial storage and transmission, vs. space-based wireless power transmission. Instead both are lumped into per kW-hr transmission costs c_T and c'_T, where it is assumed that c_T/c'_T is the same ratio χ as for space vs. Earth PV panel costs. In fact, SSP has no analog of the significant energy storage requirements for TSP, and wireless transmission obviously has no wires that need installation and maintenance. Both of these, given TSP location dependence and intermittency, add significant capital costs, \$2,000/kW or more for storage, \$10,000/kW or more for several thousand miles transmission, with current technology. Fetter's suggestion to use wireless power transmisison as an Earth-space-Earth "backstop" may make sense, but losses would be somewhat greater than for just space-Earth transmission, and the doubled distance means double the capital cost for transmitters and receivers (for a given size ratio and wavelength, they scale linearly with distance). So even with Fetter's "backstop", c_T/c'_T could well be less than 1/2. In reality we have no firm basis for speculation on these numbers without considerable further R&D on wireless power transmission, and of course refinement of terrestrial energy storage and transmission technologies. So Fetter's third and fourth conditions on relative transmission and O&M costs have insufficient basis in data at this point to draw any conclusions.

The final major issue is launch costs, which are indeed far from zero. However, commercial services are already selling low earth orbit launches for \$5,000/kg, rather than the \$10,000 Fetter cites, and one new contender, Space-X, claims it will be able to launch for \$3,000/kg soon. NASA's Space Launch Initiative, before it was recently terminated, was looking at new technologies that could provide \$1,000/kg launches; a number of other promising approaches, for example efficient two-stage launch with a reusable air-breathing hypersonic first stage, seem to be languishing only for a lack of R&D funding. The National Research Council report [8] noted that chemical rocket fuel was only needed for launch to low earth orbit; the additional energy needed for travel to geosynchronous orbit can be met (especially for a solar power satellite) through solar electric propulsion, demonstrated recently on the European SMART-1 craft. There is no physical reason why space launch continues to be so expensive; the main problem seems again one of market size. A major effort in space solar power would at least greatly expand the launch market.

The second component of launch costs is mass to launch. Thus far most satellites launched, other than the international space station, have had power levels on the order of several kW, i.e. at most a few dozen square meters of solar cell material. The best mass ratio launched so far was probably for NASA's Deep

Space-1 solar electric propulsion craft, at about 20 kg/kW. The same company that developed those has new solar panels available for just 5 kg/kW (in both cases using Fresnel lens concentrators with GaAs cells). A lower bound on solar panel mass would likely be the thin mylar material deployed to several hundred square meters in the Planetary Society's Cosmos-1 solar sail craft, at 0.02 kg/m^2, or less than 0.1 kg/kW for 20% efficient cells. Power conversion and transmission components also need to be factored in, but there are some proposed designs (high voltage, embedded waveguide or fiber optic, local phased array-style microwave beaming) with mass estimates as low as 1 kg/kW. There seems no physical reason either solar cells or transmission components should have significantly more mass than the Cosmos-1 craft; an overall mass of 1 kg/kW looks achievable, with sufficient R&D effort. A completely different alternative here are the proposals to use the elements of the Moon or asteroids in SSP construction. This has the effect of requiring launch of manufacturing facilities, rather than the final product; there are only wild guesses at this point on the mass ratios, but this could potentially (for a higher startup cost) lower Earth launch mass to well below 1 kg/kW.

It is also possible transmission efficiencies could be well above the 40% assumed by the NRC report [8]; doubling transmission efficiency would cut all the cost numbers in half, making it even easier to meet the competitive requirements. There hasn't been much real experience with wireless power transmission since William Brown's [9] early experiments, which saw DC to DC efficiencies of over 60%; a project for wireless transmission over about half a mile in Reunion Island expects 57% efficiency from one grid to the other [10]. It's impossible at this point to estimate these numbers accurately without some real R&D effort. A demonstration plant would greatly reduce this and many other uncertainties in the economic analysis.

In summary, there are four technology challenges in the standard scenario for SSP where there are enormous uncertainties in what may be technically achievable:

1. χ, the ratio of space to terrestrial PV module costs, is currently several hundred. Can we achieve $\chi < 3$ as seems needed for SSP to compete with TSP?

2. ϵ, the efficiency for wireless power transmission; is $\epsilon = 0.4$ practically achievable over tens of thousands of km? How high can it go?

3. M - the mass per peak kW of the solar modules and transmission system: the best currently deployed has M about 20 kg/kW; commercial modules of 5 kg/kW seem to be available. Is 1 kg/kW practically achievable? Could we go lower?

4. C_L - launch costs. Is the \$1000/kg NASA projected for SLI actually achievable? How much lower can we get?

Obviously SSP has some challenges - order of magnitude scale improvements needed in several immature technologies, and significant improvement in PV costs via mass production. But TSP also needs an order of magnitude improvement in cost for much more mature technologies in order to compete with other base power options. Speculation about which of these is more likely to happen over the next decade or two seems premature; rather we should be investing in the R&D, building demonstration projects, and pursuing other technology development incentives to make our choices clearer[4].

The new international "contraction and convergence" plan[11], which seems likely to replace the Kyoto accord as a more complete solution to the CO_2 problem, calls for replacement of almost all fossil fuel use by 2050. Aside from the relatively dubious concept of carbon sequestration with coal, for base power production the only multi-terawatt scale options seem to be fission, fusion, TSP, and SSP [12]. Fission is by far the most well-established of those four, but it may be more limited than we think - a recent MIT analysis[13] sees at most a tripling of world-wide nuclear power installations to 1500 GW capacity over the next 50 years, just to maintain nuclear power at roughly the 20% of electric power it generates today. Given the severity and urgency of the energy transition problem, and the fact that multi-trillion-dollar investments will be required, technologies in support of all four energy options (along with carbon sequestration) should be generously funded. SSP and TSP would both benefit from PV-related R&D funding; other R&D areas for SSP include wireless power transmission, lightweight space structures, and cost effective space launch, all of which could have significant spinoffs to other areas (for example, communications satellite capabilities) as well. Funding this range of technologies adequately, at least at the billion-dollar per year level that fission and fusion currently receive, will be essential to our future prosperity.

References

[1] "Energy for Society from Space", by Arthur Smith, Physics and Society, October 2003.

[2] "Space Solar Power: An Idea Whose Time Will Never Come?", by Steve Fetter, Physics and Society, January 2004.

[3] See http://www.aps.org/units/fps/energy/ for a list of contributions by physicists to the "Energy and Environment debate".

[4] *Innovative Strategies for CO_2 Stabilization*, edited by Robert G. Watts, Cambridge University Press, 2002.

[5] The National Ignition Facility, to be completed in 2008, is currently funded at about $2.25 billion for construction, with GAO cost estimates of $4 to $5 billion. Total thermal output is less than 200 MW, or 67 MW electric, for a capital cost over $30,000/kWe. ITER, projected to be online in about 2013, the top priority for research funding at the DOE's Office of Science. Costing over $5 billion, ITER will produce 400 MW thermal power, or over $40,000/kW electric.

[6] 1998 electricity market structure, from the US Energy Information Administration: See
http://www.eia.doe.gov/cneaf/electricity/chg_stru_update/chapter3.html

[7] "Renewable Energy Annual 2002" report, November 2003, from the US Energy Information Administration.

[8] "Laying the Foundation for Space Solar Power: An Assessment of NASA's Space Solar Power Investment Strategy" (2001) - National Research Council; see
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[10] J. D. Lan Sun Luk et al., "Point-to-point wireless power transportation in Reunion Island" 48th International Astronautical Congress, Turin, Italy, 6-10 October 1997 - IAF-97-R.4.08

[11] Contraction and Convergence, from the Global Commons Institute (2003), See:
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[12] M. Hoffert et al., “Advanced Technology Paths to Global Climate Stability: Energy for a Greenhouse Planet”, Science Vol. 298, p. 981 (2002).

[13] John Deutch, et al., “The Future of Nuclear Power” (2003)
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