Space Solar Power: An Idea Whose Time Will Never Come?

Arthur Smith laments the lack of attention to space solar power (SSP),[1] but SSP cannot compete with solar power based on earth. The advantage of SSP is a large and constant solar flux: 1.37 kW m^{-2} or 12,000 kWh m^{-2} y^{-1}. This is about five times higher than the average flux in sunny areas on the earth's surface, such as the American southwest.[2] The larger solar flux in space cannot compensate, however, for the cost of placing systems in orbit and losses in transmitting the electricity back to earth.

Smith correctly states that earth-based systems suffer from the day-night cycle and cloud cover, and the consequent need for energy storage or intercontinental transmission. But earth-based solar systems could supply up to 20 percent of U.S. electricity demand[3]—the fraction currently provided by nuclear or hydro—without storage or intercontinental transmission. Even if solar was used to meet 75 percent of electricity demand—an unlikely scenario—only about half of the solar electricity produced by earth-based systems would have to be stored or transmitted over intercontinental distances. By comparison, 100 percent of SSP electricity would have to be transmitted wirelessly to earth, with an end-to-end efficiency of perhaps 40 percent.[4] SSP transmission is likely to be less efficient than earth-based storage or transmission.[5] SSP transmission technologies would, however, provide a backstop for intercontinental transmission (via reflectors in orbit), ensuring that SSP transmission could not be significantly cheaper or more efficient than storage or intercontinental transmission of solar electricity generated on earth.

To see that SSP is highly unlikely to be competitive with earth-based solar power, consider only the costs of the photovoltaic arrays. In order for SSP to be less expensive than earth-based systems

$$\frac{C_{PV} + C_L M}{\varepsilon S} < \frac{C'_{PV}}{\left[1 - f\left(1 - \varepsilon'\right)\right] S'} \qquad (1)$$

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[1] Arthur Smith, "Energy for Society from Space," *Physics and Society*, October 2003; Arthur Smith, "Letters: Energy Possibilities: Windows, Windmills, and Satellites," *Physics Today*, October 2002.

[2] Much of the southwest receives more than 2400 kWh m^{-2} y^{-1} of total solar radiation on a south-facing surface tilted at the latitude angle (or, for concentrating systems, direct radiation on a sun-tracking surface), as do vast areas of northern and southern Africa, west Asia, and Australia, and significant areas in Chile and Argentina. See NASA, "Surface Meteorology and Solar Energy," http://eosweb.larc.nasa.gov/sse.

[3] Author's estimate; also see review in H. Ishitani, T.B. Johansson, et al., "Energy Supply Mitigation Options," in Robert T. Watson, Marufu C. Zinyowera, and Richard H. Moss, eds., *Climate Change 1995: Impacts, Adaptations and Mitigation of Climate Change* (Cambridge University Press, 1996), p. 617.

[4] Laying the Foundation for Space Solar Power: An Assessment of NASA's Space Solar Power Investment Strategy (Washington, DC: National Academy Press, 2001).

[5] Options for electricity storage include pumped hydro, compressed air, batteries, and reversible fuel cells, with round-trip efficiencies of 60-75%; costs for compressed air storage are estimated at ≈$0.01 kWh^{-1}. Intercontinental transmission is possible using high-voltage DC lines at efficiencies of 60-80% over distances of 5,000 to 10,000 km, albeit at high cost (≈$0.01 kWh^{-1} per 1000 km). Superconducting storage rings or transmission lines would have much higher efficiencies. See Bent Sorensen, *Renewable Energy* (Academic Press, 2000), p. 522-584.

where C_{PV} and C'_{PV} are the installed unit costs of photovoltaic arrays in space and on earth ($ kW_p^{-1}),[6] C_L is the unit cost of placing mass in orbit ($ kg^{-1}), M is the unit SSP system mass in orbit ($kg\ kW_p^{-1}$), S and S' are the annual solar fluences on arrays in space and earth ($kWh\ y^{-1}$), ε is the end-to-end transmission efficiency of the SSP system, ε' is the end-to-end intercontinental transmission efficiency or round-trip storage efficiency for earth-based generation, and f is the fraction of earth-based solar generation that is transmitted very long distances or stored. Assuming S/S' = 5 and solving for C_LM, we have

$$C_L M < 5\rho C'_{PV} - C_{PV} \tag{2}$$

where ρ, the efficiency ratio, is given by

$$\rho = \frac{\varepsilon}{1 - f(1 - \varepsilon')} \tag{3}$$

The fraction of solar electricity generated on earth that is stored or transmitted very long distances, f, depends primarily on the fraction of total electricity demand met by solar; if this is small (<20%), then $f \approx 0$ and $\rho \approx \varepsilon$. If solar supplies all U.S. demand, a comparison of the time correlation between U.S. demand and sunshine in the southwest suggests $\rho \approx \varepsilon/\varepsilon'^{0.55}$. If $\varepsilon' = \varepsilon = 0.4$ (a very pessimistic assumption for earth-based storage/transmission), then $0.4 < \rho < 0.65$.

Space-based photovoltaic arrays will not cost less than the same arrays based on earth, so $C_L M < C'_{PV}(5\rho - 1)$. In order to be economically competitive with other sources of electricity, it is generally believed that C'_{PV} must fall to $1000 kW_p^{-1}. Thus $C_LM < $1000 to $2300 kW_p^{-1}, where the lower limit is considerably more realistic than the upper limit.

The current state-of-the-art for solar arrays for spacecraft is $M > 10\ kg\ kW_p^{-1}$. Although improvements are possible using very lightweight materials and/or concentrating lenses, it is unlikely that the total system mass, including structural elements and power handling and transmission systems, would be less than $5\ kg\ kW_p^{-1}$. Launch costs therefore must be less than $200 to $460 kg^{-1}. For comparison, the current cost to low-earth orbit is about $10,000 kg^{-1}. Thus, even a very optimistic analysis requires that launch costs fall by a factor of 20 to 50 simply to allow SSP to break even with terrestrial solar power.

If space-based systems cost more than earth-based systems, as seems almost certain, the comparison becomes even less favorable for SSP. As indicated by equation (2), if space-based photovoltaic arrays cost two to three times more per peak kilowatt than earth-based systems, SSP would not be cost-effective even if launch cost or system mass were zero. Today, large space-based arrays cost 500 times more than earth-based arrays per peak kilowatt.[7]

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[6] Photovoltaic costs typically are given in dollars per peak kilowatt (kW_p), where kW_p is the electrical output when the incident solar flux is $1\ kW_s\ m^{-2}$; it is equal to cost per unit area ($ m^{-2}) divided by efficiency ($kW_e\ kW_s^{-1}$). Thus, $ $kW_p^{-1} = $ kW_s\ kW_e^{-1}\ m^{-2}$.

[7] The solar arrays for the International Space Station cost about $2.4 million kW_p^{-1} ($450 million for about 250 kW or 180 kW_p). For comparison, the installed cost of large earth-based arrays is currently about $5,000 kW_p^{-1}.

If the costs of transmission and operation and maintenance are higher for space-based systems, the situation for SSP is worse still. If c_T and c_{OM} are the costs of transmission and operation and maintenance per kilowatt-hour of electricity ($\$ \text{ kWh}^{-1}$) produced by SSP and c_T' and c_{OM}' are the corresponding costs for earth-based systems, equation (2) becomes

$$C_L M < 5\rho C_{PV}' - C_{PV} - \frac{S}{F}\left(c_T - f\rho c_T'\right) - \frac{S}{F}\left(c_{OM} - \rho c_{OM}'\right) \tag{4}$$

where F is the fixed charge rate (y^{-1}). Assuming $C_{PV}' = \$1000 \text{ kW}_p^{-1}$, $c_T' \approx c_{OM}' \approx c'$, and that $Sc'/F = \$500 \text{ kW}_p^{-1}$ (i.e., transmission/storage plus O&M costs are equal to capital costs),[8] then

$$C_L M < 500\left(11\rho - 2\frac{C_{PV}}{C_{PV}'} + f\rho - \frac{c_T}{c'} - \frac{c_{OM}}{c'}\right) \approx 500\left[\rho(11+f) - 4\chi\right] \tag{5}$$

where χ is the average cost ratio of space-based to earth-based systems (assumed to be equal for the array, transmission, and operation and maintenance costs).

As noted above, if solar supplies all electricity demand and $\varepsilon = \varepsilon' = 0.4$, then $f \approx 0.65$ and $\rho \approx 0.65$. If $\chi = 1$ (i.e., space-based systems are no more expensive than earth-based systems), then $C_L < \$350 \text{ kg}^{-1}$ for $M = 5 \text{ kg kW}^{-1}$; if $\chi > 2$ (costs are twice as high for space-based systems), then $C_L M < 0$ and SSP cannot compete regardless of launch cost or system mass. If solar supplies 60 percent of total demand and $\varepsilon' = 0.6$ ($f \approx 0.3$, $\rho \approx 0.45$), then $C_L < \$100 \text{ kg}^{-1}$ for $\chi = 1$ and $M = 5 \text{ kg kW}^{-1}$, and $C_L M < 0$ for $\chi > 1.3$. Finally, if solar supplies less than 20 percent of total electricity demand ($f \approx 0$, $\rho \approx 0.4$), then $C_L < \$40 \text{ kg}^{-1}$ and $C_L M < 0$ for $\chi > 1.1$.

In summary, SSP could compete with earth-based solar power only if *all* of the following conditions are met:

- solar supplies ~100% of total electricity demand;

- the cost of space-based solar arrays is reduced to $\$1000 \text{ kW}_p^{-1}$ and earth-based arrays do not cost less than space-based arrays;

- SSP transmission is no less efficient and no more expensive than storage or intercontinental transmission of electricity generated by earth-based systems;

- SSP operation and maintenance is no more expensive than operations and maintenance of earth-based systems;

- total on-orbit system mass is less than 5 kg kW^{-1}; *and*

- launch cost (currently about $\$10,000 \text{ kg}^{-1}$ to low-earth orbit) is less than $\$350 \text{ kg}^{-1}$.

Much of the discussion surrounding SSP has focused on the last of these conditions. With chemical propellants, very low launch costs can be achieved only with a reusable vehicle. At

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[8] This corresponds to F = 0.12 y^{-1} (an interest rate of 0.1 y^{-1} over a lifetime of 20 y) and c' = $\$0.005 \text{ kWh}^{-1}$.

today's prices, propellant for a reusable vehicle would cost about $50 per kilogram placed into low-earth orbit (LEO) and 150 kg^{-1} for geosynchronous orbit (GEO).[9] Achieving a total cost of $350 kg^{-1} would therefore require a total-to-fuel cost ratio of 7:1 for LEO and 2:1 for GEO. To put this into perspective, the cost ratio for the U.S. air freight industry is about 4:1.

The probability the SSP could simultaneously meet all of the conditions outlined above and produce electricity more cheaply than solar arrays on earth is so small that any significant expenditure of federal funds for research and development on this concept would be unwise and unwarranted.

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[9] The propellant-to-vehicle mass ratio for a single-stage-to-orbit vehicle $m_p/m_v = \exp(\Delta v/v_e) - 1$, where Δv is about 10 km s^{-1} for a 1000-km altitude near-polar orbit (including losses due to gravity and air resistance) and v_e is the exhaust velocity. Assuming $v_e = 3.8$ km s^{-1} for O_2/H_2, $m_p/m_v = 12.6$; assuming $v_e = 2.9$ km/s for O_2/RP-1, $m_p/m_v = 29$. If 20 percent of the vehicle mass is payload, the propellant-to-payload mass ratios are 63 and 145, respectively. Assuming an O_2/H_2 mass ratio of 6 and O_2 and H_2 costs of $0.25 and $4 kg^{-1} (current delivered prices to Kennedy Space Center), the propellant cost is $50 per kilogram of payload. Similarly, assuming an O_2/RP-1 ratio of 2.5 and RP-1 cost of $1 kg^{-1}, the propellant cost is $70 kg^{-1}. Geosynchronous orbit requires a total $\Delta v \approx 14$ km s^{-1}, giving propellant-to-payload ratios of 190 for O_2/H_2 and 580 for O_2/RP-1, and propellant costs of $150 and $270 kg^{-1}.