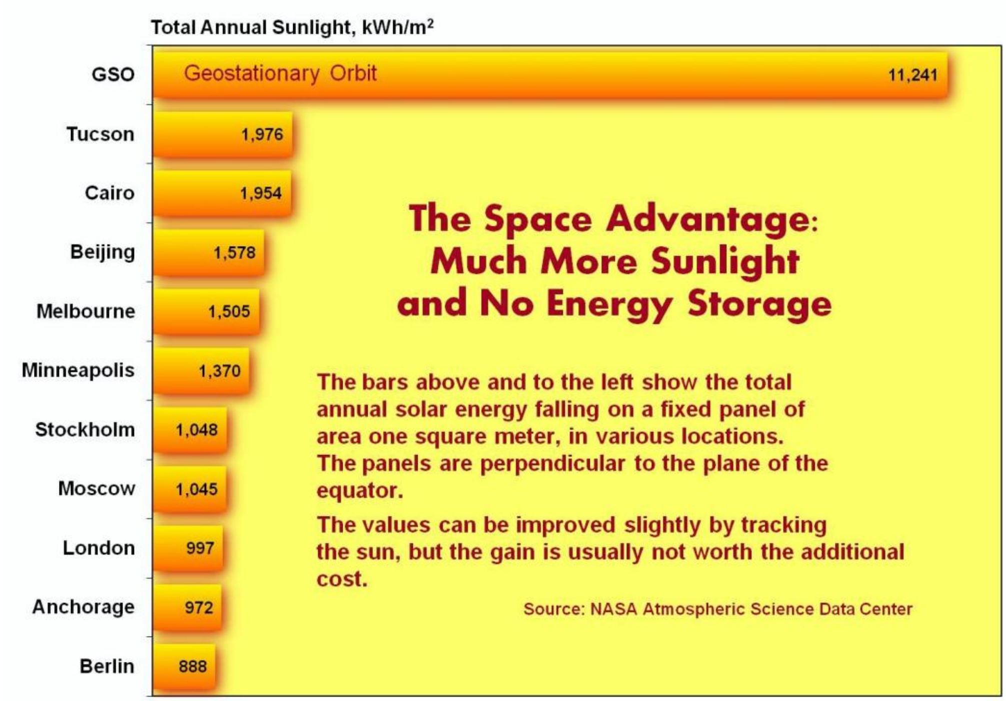

Solar High: Energy for the 21st Century

Solar High Study Group

March, 2011

Meeting the growing global demand for electric power during the next 25 years will be a massive undertaking. The economies of scale in this effort can overcome the barriers to deployment of solar collectors in space, where sunlight is continuous and intense. Terrestrial solar technologies cannot compete with fossil fuels in wholesale power applications, but solar power satellites can provide clean, inexhaustible, affordable energy worldwide.

The Solar Problem

The DOE Energy Information Administration (EIA) forecasts a 50% increase in worldwide electric generating capacity by 2035, from ~ 4,650 gigawatts (GW) to just over 7,000 GW. This does not include the additional plant that may be required to enable

- replacement of obsolete or environmentally unacceptable facilities;
- widespread adoption of plug-in hybrid or fully electric vehicles;
- desalination of seawater on a large scale; and
- substantial economic growth in poor nations.

Without decisive action to reduce the cost of renewable sources (especially solar) this expansion will involve much greater consumption of coal, nuclear energy and natural gas.

Solar photovoltaic (PV) arrays are rated by their output when exposed to sunlight at its maximum intensity, 1,000 watts/sq.m. Using this measure, the present installed cost of a large array designed to feed power to the utility grid is ~ $5,000/kilowatt; the DOE hopes to reduce this to $2,000/kilowatt within 5 years. Because of nighttime, daily and seasonal variations and weather, the *average* intensity of sunlight is less than 285 watts/sq.m., even in favorable areas such as the Arizona desert. The real installed cost is therefore more than $17,500 per *average* kilowatt. A complete utility-scale system also requires extensive energy storage to compensate for the variations in sunlight, plus long-distance transmission lines to deliver power from the desert to load centers. When the inefficiencies and costs of these ancillary systems are taken into account; the cost rises to ~$37,000 per average kilowatt delivered to the load. The cost may fall to ~ $20,000/kW if the DOE meets its PV cost goals, but this is still far from competitive with fossil fueled power plants (even when external costs such as environmental impacts are included). The EIA therefore estimates that in 2035 the solar contribution to electric utilities, worldwide, will be a paltry 0.5% of their total consumption.

The Solar Solution

If we want to make solar energy affordable, we must put the collectors in space, where the sun shines 24/7 and the intensity of sunlight is 1,360 W/sq.m., 40% greater than on Earth. The best location is geostationary orbit (GSO, 35,800 km above the equator), where a satellite remains fixed relative to terrestrial sites.

The principal components of a power satellite are a large solar array and a microwave transmitter that beams power to an Earth-based receiver called a rectenna (a contraction of 'rectifying antenna'), where it is converted to standard AC. The continuous, intense sunlight in GSO means that that no energy storage is needed, and that the solar array is a factor of 8 smaller than a similar terrestrial array with the same average output. The benign operating environment, in vacuum and free fall, permits high solar concentration without complex sun-tracking mechanisms and avoids maintenance problems caused by wind, dust, rain, snow or hail.

Each satellite will deliver 2 GW to the utility grid, an output similar to a large nuclear plant. There is room in GSO for thousands of them.

The microwave flux in the power beam is insufficient to harm aircraft or birds. The rectenna area is a factor of 9 smaller than the terrestrial solar farm that it replaces; it can be located close to the intended load center; and the structure shields the ground underneath from microwaves but is largely transparent to sunlight, so that it can be used for agriculture or other purposes.

The technical feasibility of space-based solar power (SBSP) is beyond dispute. PV cells have been used in space for decades, and wireless power transmission has been demonstrated repeatedly, on Earth and in space. NASA and the DOE sponsored an extensive study of the subject in the late 1970s that found no show-stoppers, and this result has been confirmed by several major studies since then. We have been waiting for advances in space technology to reduce costs to a competitive level. That time is now.

Objections to Space-Based Solar Power

1. Space hardware is expensive. Satellite equipment is expensive because it is constructed in small quantities, by hand, in clean rooms. The mass production needed for power satellites will reduce these prices to terrestrial levels. In fact, the fabrication cost for a power satellite will be much less than for a comparable terrestrial solar power plant, because the solar array is much smaller.

The current study by the Solar High Study Group indicates that technology available now permits a Block I power satellite to be built at a hardware cost of ~$8,500 per kilowatt. Foreseeable near-term advances are expected to reduce the cost of a Block II satellite to ~$4,000/kW. Building the rectenna would add ~$1000/kW to these figures.

2. SBSP requires a major expansion of space operations. While small compared to terrestrial solar arrays of similar output, power satellites are large compared to anything yet deployed in space. Note however that the massive effort needed to build generating capacity during the next 25 years will cost trillions of dollars, regardless of the energy technologies that are used. Developing SBSP will be a relatively modest but important part of that undertaking.

3. Spaceflight is too expensive for SBSP. If the energy needed to launch a payload to low Earth orbit (LEO) could be obtained at the current retail price of electricity, the cost would be less than $1/kg. Launch is expensive only because it is infrequent, and it is infrequent because it is expensive. Air travel would be equally expensive if Boeing built only four 777s each year, and if airlines scrapped the aircraft after each flight. SBSP provides the launch market needed to escape this Catch 22.

The SpaceX Falcon 9 can launch more than 10 metric tons (MT) to LEO, at a quoted price of $5,000/kg. The recently announced Falcon Heavy, scheduled for first flight in 2012, will deliver >50 MT to LEO at an expected price of $2,200/kg. This is twice the payload of the Delta IV Heavy (the heaviest launch vehicle now available) at 20% of the cost per kilogram. At these prices, power satellites would be very competitive with terrestrial solar power, but not with fossil fueled plants.

A reasonable SBSP program would grow to a deployment rate of 10 to 20 GW per year by 2020. In that time frame, a Block II satellite supplying 2 GW to the grid is expected to have a mass in LEO of ~12,000 MT, including the propellant needed for self-powered low-thrust transfer to GSO. The required throughput from Earth to LEO is thus more than 60,000 MT per year. If the payload of the vehicle is near 50 MT, the launch campaign would involve 3 to 7 launches per day, which is large compared to present launch rates but much less than the daily flights from almost any commercial airport.

This traffic requires an equatorial launch site, because it is the only location that offers frequent windows for launch to an assembly facility in (equatorial) LEO. It also permits direct recovery of a reusable upper stage to the launch site after a single orbit.

Falcon launch vehicle stages are designed for reuse after landing in the ocean. Some modifications but no radical advances in technology would be needed to permit land recovery and reuse with minimal refurbishment. Examination of the cost factors in space launch shows that the economies of scale offered by launching reusable vehicles at the rate required for SBSP will lead to a further reduction in cost to less than $400/kg.

Space launch would thus contribute ~$2,400/kW to the cost of the system.

Conclusion

The expected cost of deploying SBSP is ~$7,400/kW, including the rectenna as well as construction and launch of Block II satellites. Amortized over an expected life of 30 years at a discount rate of 5%, the contribution of this capital cost to the delivered cost of electric energy would be 5.6 cents/kWh. SBSP is thus *much* more promising than terrestrial solar as a replacement for fossil fuels or nuclear power.

A strong US commitment to SBSP could

- Solve the energy problem permanently, in the USA and around the world.
- Offer clean, inexhaustible solar power almost anywhere on Earth.
- Restore the status of the United States as an energy-exporting nation.
- Create large international markets for export of our technology as well as energy.
- Offer greatly reduced launch costs to all users of space, including the DoD, NASA and commercial interests.
- Restore US preeminence in launch services.
- Permit explosive growth in extraterrestrial enterprises.
- Open the solar system as the domain of our species, eliminating most concerns about resource exhaustion.

Serious studies of SBSP are under way in several countries, including Japan, China, India and the European Union. Continued US neglect of this vital technology means that we will not only suffer all the economic, political and strategic consequences of abdicating our leadership in space but also abandon control of our energy future. What we do about these issues in the next few years will determine whether we will restore American initiative or become a debt-ridden, second-rate nation that must import electricity as well as petroleum.

There are three important roles for government agencies in making SBSP happen:

- NASA and ARPA-E should be working on advanced enabling technologies that can make SBSP even more effective, as NACA once did for aviation. Examples include improvements to reusable, economical rocket engines, reentry systems, gossamer space structures, and lightweight, efficient microwave transmitters.
- NASA, NOAA and the DoD should offer performance-based contracts in advance for a sufficient number of commercial launches to justify private development of suitable reusable vehicles. This will save money, compared to continued reliance on expendable launch vehicles. This policy is analogous to the use of airmail contracts in promoting the airline industry.
- The Congress should reduce risks for large private investments in power satellites by offering loan guarantees, tax holidays and other incentives.

Note that these functions do not include large upfront Federal expenditures on system studies or power satellite development programs.

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