Word count (including bio): 1895

An Isoinertial Solar Dynamic Sunsat

Philip K. Chapman[1]

December, 2008

1. Introduction

The current reference projection by the Energy Information Administration of the Department of Energy (DoE EIA) is that growth in US demand for electric power will require new generating capacity amounting to 235 GWe by 2030 (including replacement of obsolete plant).[2] If the United States ends dependence on foreign oil by widespread adoption of plug-in hybrid electric vehicles (PHEVs), charging their batteries would require up to 150 GWe in additional capacity.

Growth will be much faster in the world outside the USA, where the projection gives an increase in capacity of nearly 2500 GWe.

While conventional renewable sources (wind, terrestrial solar, biomass, etc.) can and will contribute where conditions permit, there are only four energy options that offer any realistic possibility of meeting these needs during the next several decades: nuclear power, coal, methane hydrates (under the Arctic permafrost and on continental shelves), and solar power satellites ("sunsats"). All of them will be needed -- but the first three face determined public resistance due to perceived environmental consequences.

A sunsat consists of a large solar array in geostationary orbit (GSO, 35,800 km above the equator), transmitting power in the form of microwaves to a rectenna (rectifying antenna) on Earth. The array tracks the sun, while the axis of the microwave antenna remains along the local vertical, rotating once per orbit about the orbit normal. Electronic steering deflects the beam from the nadir to the target rectenna; the maximum deflection to anywhere on the visible disk, in the north or south hemisphere, is 8.7°. The rectenna, located near the intended load, converts the energy received to standard AC.

Sunsats could provide clean, carbon-neutral, inexhaustible electric power anywhere on Earth, up to at least 60° latitude. There is room in GSO for thousands of them.

While development and deployment of sunsats on a scale commensurate with energy needs would be a major enterprise, no technological breakthroughs are required. Because there is no night or weather in GSO, the area of the array needed for a given energy

---

[1] See Appendix

[2] Data from the EIA Annual Energy Outlook 2008 and the EIA International Energy Outlook 2008, at http://www.eia.doe.gov/oiaf/aeo/aeoref_tab.html .

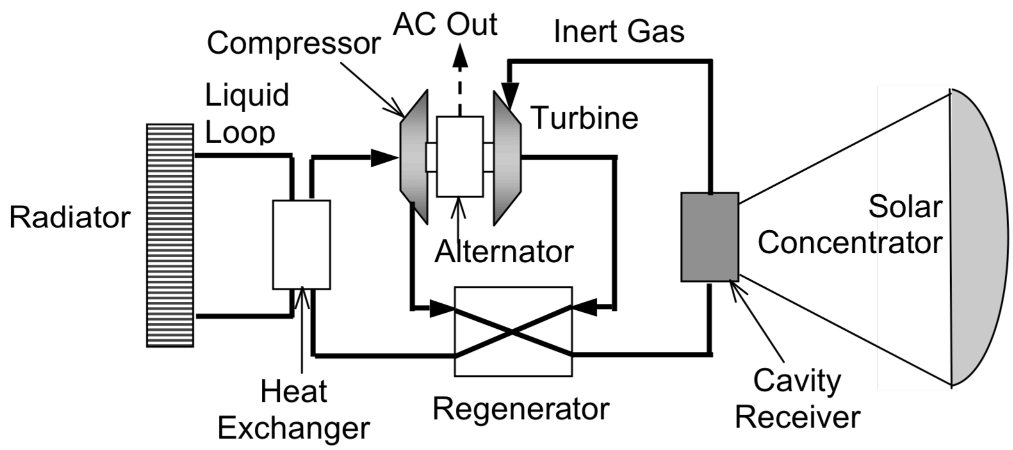

Figure 1: A Closed Brayton-Cycle Solar Turboalternator

output is less than 20% of that for a terrestrial system using the same solar conversion technology – and no energy storage is required. These factors, together with the benign operating environment in free fall and vacuum and the delivery of power near the intended load mean that the capital cost of the overall system can be considerably less than for a comparable solar power plant on Earth.

The price paid for these benefits is the need to deploy structures in space that are very large by current spaceflight standards. Whether or not sunsats can be competitive with terrestrial sources thus depends almost entirely on the feasibility of (1) a very light structure, and (2) a major reduction in space launch costs.

This paper addresses the first of these issues. A companion paper[3] shows that economies of scale in even a modest sunsat deployment program will permit launch costs of order $300/kg, using quite conventional technology.

2. The Turbo Sunsat

Most sunsat studies to date have assumed photovoltaic (PV) solar energy conversion. This is a promising avenue for future work, but the performance, mass and cost of these devices do not yet permit a cost-effective system, and the global production capacity is inadequate to supply them in sufficient quantity.

Solar-powered Brayton-cycle turboalternators offer an alternative with better performance that is available now. These generators are a mature technology, widely used in gas-fired power plants and in marine propulsion systems. Aerospace versions have also been in use for decades, in the auxiliary power units found in most large aircraft. NASA Glenn Research Center has been working for more than 30 years on spaceborne systems of this type for nuclear or solar electric propulsion, using a noble gas working fluid in a closed loop. The basic layout is sketched in Figure 1.

The compressor, alternator and turbine are mounted on the same shaft, making a very compact installation. Many of the components (including compressors, turbines and non-

[3] Chapman, P.K., *High Volume Launch to Orbit,* December 2008.

contacting gas foil bearings) are derived directly from jet engines, which routinely produce specific powers >10 kW/kg. The large jet engine industry (worldwide sales $18.5 billion in 2006) means that the manufacturing infrastructure is already in place for mass production of these generators.

The turbosunsat consists of an array of solar dynamic modules (SDMs). Each one is a self-contained generator, including a turboalternator, a deployable solar collector and a radiator. The collectors may use large Fresnel lenses or Cassegrain reflectors. In either case, the radiators are in shadow, protected from direct sunlight.

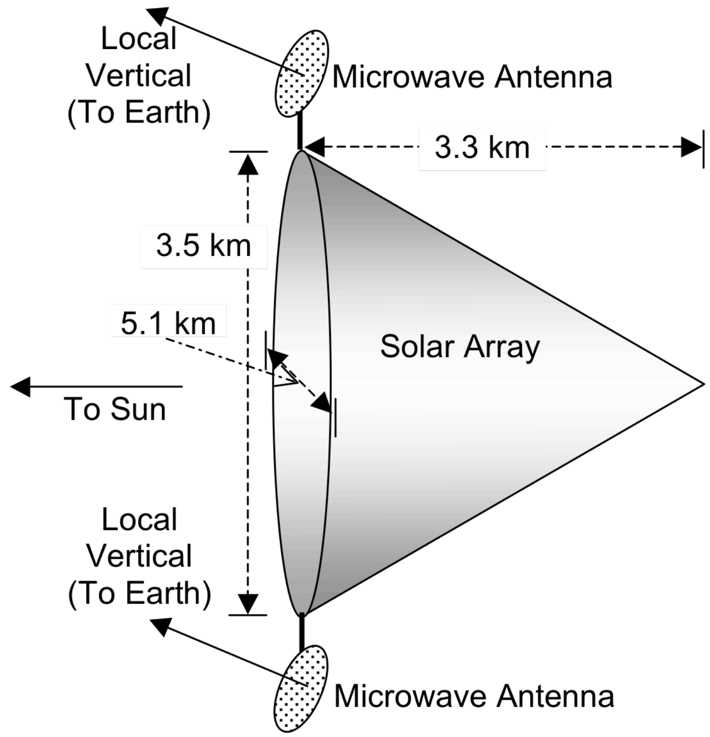

Figure 2: Isoinertial Sunsat Configuration

The SDMs are launched from Earth as separate packages, which unfold in LEO and connect together to form a complete plug-and-play sunsat array. The transmitting antennas and other components (attitude control systems, etc.) are broken into segments compatible with the launch vehicle and assembled in LEO.

Solar dynamic sunsats have substantial advantages:

- The high conversion efficiency means that the sunsat can be smaller than in other approaches, for the same power output.
- The high concentration ratio means that 99% of the collection area can consist of reflectors or Fresnel lenses with very low mass per square meter.
- The overall specific mass (kg/kW) can be less than in any photovoltaic sunsat proposed to date.
- Unlike photovoltaics, the specific mass of a Brayton-cycle turboalternator decreases as the unit power output increases.
- The alternator produces high voltage alternating current at a frequency above 1 kHz, which simplifies the power management and distribution (PMAD) system and reduces its mass.
- The AC PMAD permits inductive power transfer across the rotating joints to the microwave antenna, avoiding the need for sliprings.

- The inherent radiation tolerance enables self-powered electric propulsion for ascent through the Van Allen Belts to GSO and gives a long operational life once the sunsat is on station there.

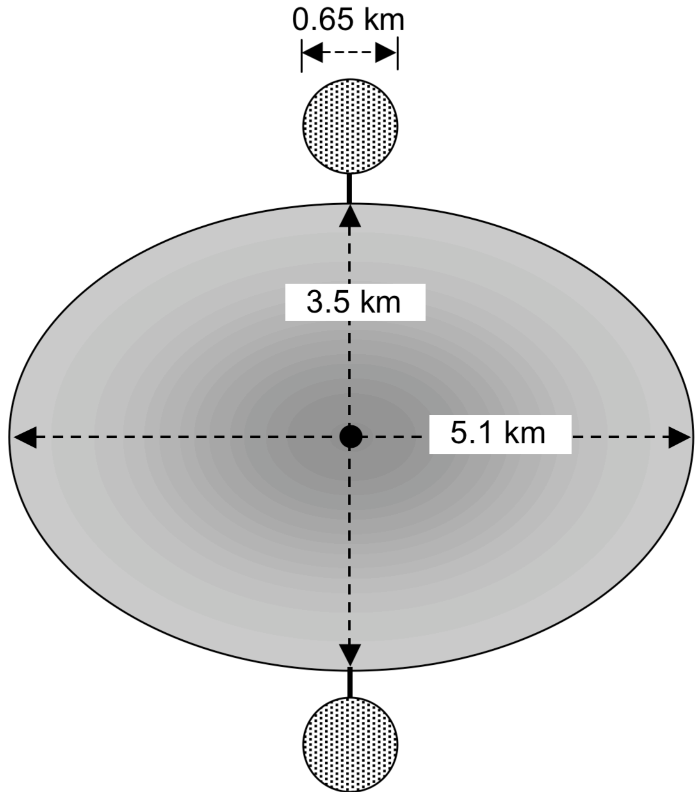

Figure 3: Sunsat Dimensions

3. The Isoinertial Sunsat

Efficient solar dynamic energy conversion requires a high source temperature (>1500 K), thus a high concentration ratio (>500), and thus accurate tracking of the sun (~0.1^{o}) in both right ascension and declination. While other solutions are possible, the easiest way to achieve this is to keep a principal axis of the sunsat pointed at the sun, while a second principal axis remains in the orbital plane. With this orientation, an annual rotation about the normal to the ecliptic is the only motion of the satellite with respect to inertial space. The angular velocity varies slightly, from 1.02°/day at perihelion (January) to 0.95°/day at aphelion.

In general, maintaining this orientation in the presence of gravity-gradient torques requires strong attitude control authority while the sunsat is at low altitude during self-powered ascent to GSO, especially if the transfer occurs near a solstice. These torques vanish if the satellite is isoinertial (i.e., if the three principal moments of inertia are all equal). The arrangement chosen here is derived from the observation that a uniform right circular conical shell is isoinertial if the semi apex angle is 25.2°.

In order to include the inertial effects of microwave antennas, the SDMs are arranged in an array in the form of an elliptic cone. To preserve inertial symmetry, the array is sized to feed two independent rectennas on Earth, via two planar phased-array microwave transmitting antennas, located outboard on the minor axis of the base of the cone. Figure 2 is a perspective sketch of the resulting system.

The cost-optimum power output of a sunsat is determined by diffraction of the microwave power beam and the maximum permissible microwave flux above the rectenna. It is assumed here that the power beam operates in the ISM band centered on 5.8 GHz. Each transmitting antenna has a diameter of 650 meters, and the power output to the terrestrial grid is 2 GW from each rectenna.

The dimensions if the sunsat are chosen (1) to provide the array area needed for the desired power output; (2) to ensure that the microwave beams do not intersect the array even at a solstice, when the axis of the cone is 23.4° above or below the orbital plane; and (3) to satisfy the isoinertial condition, given the masses of the antennas and the SDMs in the solar array. Figure 3 shows, approximately to scale, the shape of the base and the size of the transmitting antennas for this system.

Subsystem	Power out GW	Mass MT
2 Rectennas	4.00	N/A
2 Transmitters	5.52	6,900
PMAD	6.46	1,360
SDMs	6.80	8,807
Sunsat structure		1,877
Total mass in GSO		18,944
Mass ratio for orbital transfer		1.1
Mass on LEO		20,838
Specific mass (kg/kW)		5.2

Table 1: Turbo Sunsat Masses

4. Potential Performance

In 1999, Lee Mason of NASA Glenn Research Center predicted[4] that foreseeable advances in technology would permit building a complete SDM with an output of 10 MWe and a specific mass below 1.4 kg/kWe. The calculated efficiency of the Brayton turboalternator, from heat in to AC power out, was 47.1%, and the overall conversion efficiency from sunlight to electricity was 35.1%. Since these estimates were published, almost all the specified advances have in fact occurred.

A survey in 2002[5] estimated the specific mass of the microwave antenna system (using magnetrons) as 1.25 kg per kW of beam power, and the conversion efficiency as 85.5% (electric to microwave power). The nominal mass breakdown shown in Table 1 is based on these values, Mason's data and estimates of other major component masses.

Taking into account losses in the PMAD system, in conversion to microwaves and in transmission to and conversion by the rectenna, delivering a total of 4 GW to the grid requires 680 SDMs @ 10 MWe each, with a total array aperture of 14.1 sq.km. If sunsats are to make a significant contribution to future energy needs, production lines will be needed that can manufacture several thousand SDMs each year and many square kilometers of thin-film solar concentrator.

While much more work is needed to define a realistic isoinertial solar dynamic sunsat, these preliminary results are very encouraging, offering the possibility of a specific mass in LEO of order 5 kg/kW. If the cost of launch to LEO falls to ~$300/kg, deployment of the system in space will add <$1600/kW to the non-recurring cost of each sunsat. Amortized over a life of 30 years at a discount rate of 6%/year, launch will add <1.4 ¢/kWh to the price of energy delivered to the grid.

---

[4] L. Mason, "A Solar Dynamic Power Option for Space Solar Power," 34th Intersociety Energy Conversion Engineering Conference, Vancouver, August, 1999. Available at http://gltrs.grc.nasa.gov/reports/1999/TM-1999-209380.pdf

[5] J.O. McSpadden & J.C. Mankins, "Space solar power programs and microwave wireless power transmission technology," IEEE Microwave Magazine, **3**, #4, Dec, 2002, pp 46-57.

Appendix: Biographical Note

Phil Chapman is a physicist and astronautical engineer, born in Melbourne, Australia. After earning a B.Sc. in physics at Sydney University, he spent the International Geophysical Year in Antarctica, and was invested with the British Polar Medal for services while wintering at a remote two-man camp. He migrated to the US in 1961 and earned an M.S. in Astronautics and Sc.D. in physics from MIT, before being selected by NASA as a scientist astronaut (and the first foreign-born astronaut). After jet pilot training with the USAF, he served as Mission Scientist for Apollo 14. Since then, he has been involved in a wide variety of studies related to energy systems, spaceflight and geophysics. In particular, he worked at Arthur D. Little, Inc., with Dr Peter Glaser, inventor of the sunsat concept, during the DoE/NASA study in the late 'Seventies.

Philip K. Chapman, Sc.D.
416 Ives Terrace
Sunnyvale, CA 94087

Phone: 408 749 8789
Mobile: 408 406 3830
Email: philchapman@sbcglobal.net