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Energy Analysis of the Solar Power Satellite

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Summary. The energy requirements to build and operate the proposed Solar Power Satellite are evaluated and compared with the energy it produces. Because the technology is so speculative, uncertainty is explicitly accounted for. For a proposed 10-gigawatt satellite system, the energy ratio, defined as the electrical energy produced divided by the primary nonrenewable energy required over the lifetime of the system, is of order 2, where a ratio of 1 indicates the energy breakeven point. This is significantly below the energy ratio of today's electricity technologies such as light-water nuclear or coal-fired electric plants.

The Solar Power Satellite (SPS) is immune to storage problems that befall many solar technologies since the collector is situated 36,000 kilometers (22,000 miles) from the earth's surface in geosynchronous orbit—far from the effects of clouds, and affected by the earth's shadow less than 5 percent of the time. The SPS has been discussed several times since its introduction in 1968 [for example, see (*1–3*)]. Physically and economically, it is a large project. A 10-gigawatt facility would involve a nominal 100-km^2 space array where sunlight is collected, converted first to electric energy and then to microwaves, and beamed to a nominal 100-km^2 receiving antenna (rectenna) on the earth, and there converted again to electricity for distribution (see Fig. 1). The cost of the first SPS is estimated at $60 billion, with subsequent decreases in unit price as more are produced (*4*).

The SPS is an active political issue, with congressional hearings in April 1978 (*5*) and the formation of the Sunsat Council to promote SPS funding (*3*). Besides economics, other issues have been raised, such as (i) possible materials bottlenecks [current design indicates that one 10-GW SPS would require 0.13 percent of the world's aluminum reserves (*6*)], (ii) atmospheric pollution from the many launch flights required [estimated at 500 per SPS (*7*)], (iii) disruption of the ionosphere by microwaves and resulting impairment of radio communications and radio astronomy (*8*), and (iv) possible health effects of spillover and accidentally straying microwaves.

Behind all of this is a fundamental question that every federally funded energy technology is subject to by statute (*9*), that of how much energy the SPS will produce compared to the energy required to construct and maintain it. Even though the SPS is a solar-based technology for which the fuel is renewable and free, its large materials and transportation requirements potentially could require much nonrenewable energy. In this article we report the results of such a comparison, a so-called net energy analysis of the SPS.

Net Energy Analysis

The usefulness of net energy analysis has been widely criticized (*10*). We acknowledge many of its shortcomings (*11*), but we still feel that it is one of many valid inputs to energy policy decisions. We stress, however, that it becomes more important as the technology under study approaches the net energy limit, where energy produced equals energy used (by whatever definition is finally agreed upon). At least two proposed solar-based technologies are close to that limit: gasohol, which we discuss elsewhere (*11, 12*), and the SPS. For both of these, the net energy ratio is less than approximately 2, where a value of 1 denotes the limit. Other, more conventional technologies, such as light-water reactors or coal-fired electric plants, have similarly defined energy ratios of order 5 to 15. It therefore seems likely to us that energy analysis will be of relatively greater use for the SPS than for, say, a fossil electric plant burning western coal.

We have analyzed a 10-GW SPS, as specified and inferred in (*4, 8, 13–15*), using various techniques and results from energy analysis (*16*). In general, we explicitly cover the direct and indirect energies required to produce materials and services. As outlined below, we have tried to be attentive to the "classical" problems of energy analysis [for example, see (*11*)].

1) The system boundary is specified (for example, the energy cost of research and development is not included).

2) An effort has been made to be consistent in the treatment of electricity versus primary fuels.

3) Care has been taken to separate the concept of energy payback from that of energy balance.

4) The sensitivity of the conclusions to uncertainties in input data has been calculated.

The SPS is a future technology for which requirements of materials and en-

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ergy are rather speculative. Consequently, we used an aggregated model to calculate energy requirements. As shown in Table 1 and Fig. 1, we divided the SPS into six modules (such as space transportation), each of which is specified by requirements for ten materials (such as silicon), with overall system requirements subject to eight parameters (such as duty cycle). The input variables are summarized in Table 2.

Considerable differences of opinion exist about these modules. For example, will the space solar array be assembled in low earth orbit (500 km in height) and transported intact to geosynchronous orbit (36,000 km) by using an ion thruster, or will it be assembled in geosynchronous orbit (as we have assumed)? Will maintenance actually be performed, or will significant degradation of output be accepted (or occur in spite of maintenance)? How productive can workers be in a space environment, floating in space suits or protective vehicles? Will the launch site be located on the equator or in Florida?

We include all fabrication and transportation of components in space and on the ground, and maintenance. Not included are construction of an electric distribution system on the earth, construction of additional power stations to provide reserve margin, research and development, and decommissioning. In addition, we assume that the SPS is constructed using today's energy supply infrastructure, which is dominated by fossil fuels. If there were a sufficient number of SPS's that some of the energy needed to manufacture an SPS were itself produced by an SPS, the definition would have to be modified. This is a standard problem in energy analysis (*17*).

Ultimately, the analysis is limited by data uncertainty. In Table 2 we list the estimated uncertainty in the 18 variables. The energy intensities represent all primary nonrenewable energy required in the chain of extraction to fabrication of the various materials with present technology. The uncertainties represent limits of energy analysis today, as well as our estimate of the effect of future technological changes. We have determined the effect of these uncertainties on the results (the energy ratio) by Monte Carlo

Table 1. Specifications of modules for a 10-GW Solar Power Satellite.

Material*	Module 1 ground transportation (MT/MT-km)†	Module 2 space transportation (MT/MT)	Module 3 solar cells (MT)	Module 4 transmitter (MT)	Module 5 rectenna (MT)	Module 6 space construction equipment (MT)
8. Aluminum	0	0.6	9,300	4,370	300,000	100
9. Concrete	0	0	0	0	2,860,000	0
10. Silicon	0	0	36,750	0	0	0
11. Steel	0	0	0	8,370	2,900,000	0
12. Rocket propellant 1	0	10	0	0	0	0
13. Liquid hydrogen	0	2.6	0	0	0	0
14. Liquid oxygen	0	45	0	0	0	0
15. Electronic parts	0	0	0	0	300,000	0
16. Other	0.00002	0.00294	11,500	2,330	0	0
17. Argon	0	0	0	0	0	0
Total		58.2	57,550	15,070	6,360,000	100

*Numbers refer to variables in Table 2. †Weights are in metric tons (MT); 1 MT = 10^3 kg. Weights of modules 2 to 6 are transported on the ground; weights of modules 3, 4, and 6 are transported on the ground and in space. In our calculation, space components are assumed to be transported 4000 km on the ground (for instance, southern California to Florida) and rectenna components to be transported 400 km.

Table 2. Input variables.

	Variable	Value*	Comments	Sources
1.	Solar cell half-life	25 ± 5 years	Implies that SPS power decreases with time	Estimated
2.	Solar cell efficiency	0.125 ± 0.025		(*8*)
3.	Rectenna area	45 ± 15 km^2	Dependent on microwave standards	
4.	Solar cell thickness	0.175 ± 0.075 mm		(*8*)
5.	Duty cycle	0.925 ± 0.025	Higher than nuclear or fossil	(*8*)
6.	Cell attrition	0.05 ± 0.05	Dependent on space assembly concept employed	Estimated
7.	Grid efficiency	0.95 ± 0.05	As measured with respect to today; transmission distance longer	Estimated
8.	Energy intensity, aluminum	74,500 ± 8,500 kWh/MT†		(*23*)
9.	Energy intensity, concrete	360 ± 50 kWh/MT		Calculated
10.	Energy intensity, silicon	13,950,000 ± 12,050,000 kWh/MT	Poorly known, but large and important	(*8*)
11.	Energy intensity, steel	16,500 ± 2,500 kWh/MT		(*23*)
12.	Energy intensity, rocket propellant 1	14,500 ± 500 kWh/MT	Similar to kerosene	Calculated
13.	Energy intensity, liquid hydrogen	185,000 ± 45,000 kWh/MT		(*8*)
14.	Energy intensity, liquid oxygen	3,750 ± 450 kWh/MT		Calculated
15.	Energy intensity, electronic parts	69,500 ± 17,500 kWh/MT		Calculated
16.	Energy intensity, other	74,500 ± 8,500 kWh/MT		Calculated
17.	Energy intensity, argon	9,000 ± 2,000 kWh/MT		Calculated
18.	Energy intensity multipler, transportation	1.0 ± 0.5	Especially to account for space transportation uncertainty	Estimated

*Values are assumed to have a truncated Gaussian distribution such that before truncation, P = .90 that the value falls in the given range. †Units of variables 8 to 17 are primary kilowatt-hours per metric ton; that is, a nonredundant sum of coal, crude oil, gas, hydro, and nuclear power. Hydro may or may not be considered renewable depending on factors such as reservoir siltation rates. We consider it nonrenewable. In any case, it is a small contribution, about 4 percent of total primary energy as used here.

Table 3. Energy ratio for the Solar Power Satellite and several conventional electrical technologies.

Technology	Energy ratio	
	Fuel included	Fuel excluded
Coal-fired power plant*	0.31	7.7
Light-water nuclear plant*	0.24	4.8
Combined cycle coal-fired plant*	0.38	14
Solar Power Satellite		
Mean	2.1	2.1
Median	1.8	1.8
Mode	1.6	1.6
Standard deviation†	0.8	0.8
Mean deviation†	0.6	0.6

*Source: (*24*). †Standard deviation in $X = \left[\sum_{i=1}^{5000} (X_i - \text{mean})^2/(5000 - 1)\right]^{1/2}$.

Mean deviation $= \sum_{i=1}^{5000} |X_i - \text{mean}|/(5000 - 1)$.

Both the standard deviation and the mean deviation are calculated from a Monto Carlo simulation of 5000 runs.

simulation. Values for the 18 variables were chosen randomly from the indicated intervals (*18*) and a value for the energy ratio was then calculated. Another set of 18 random choices was inserted and another value was calculated. This was repeated 5000 times, producing a frequency distribution of values for the energy ratio as shown in Fig. 2.

The details of the calculation are given in (*19*). It should be noted that we explicitly assumed that the power output decays exponentially with time because of degeneration of solar cells. We chose a 25-year nominal half-life of the cells (and hence of power) and a 30-year productive lifetime for the whole facility. We are not certain of the exact form of degradation, but consider the form we used to be justified in qualitative terms. It has been reported (*20*) that the decay is exponential in time for a constant particle flux (*21*).

Energy Ratio

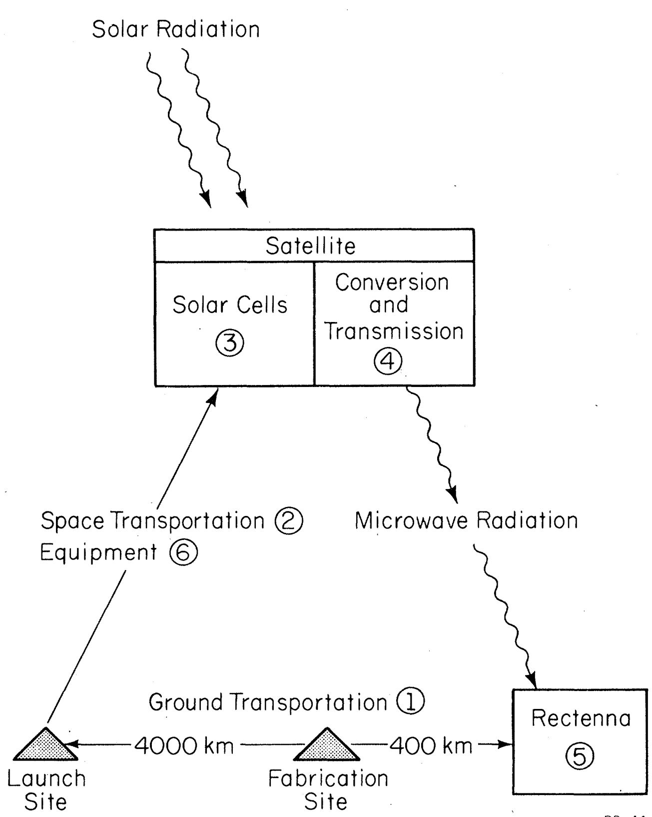
Strictly speaking, the net energy picture is totally given by a detailed knowledge of the power required and produced as a function of time, the so-called power curve. Various shortcuts are used to portray aspects of it: the energy ratio or the payback time. Energy ratio and payback time are not related uniquely (*11*) and here we use only the energy ratio (ER), which we define as the electrical energy delivered over the lifetime of the facility divided by the primary nonrenewable energy required to construct the facility and operate it over its lifetime.

Values for ER are given in Table 3. Note that they incorporate the uncertainty analysis, the results of which are

Table 4. Percentage contributions of the six modules and of maintenance to the energy requirements of the Solar Power Satellite (*25*).

Factor	Contribution (%)
Ground transportation	3.8
Space transportation	7.7
Solar cells	65.7
Transmitter	0.1
Rectenna	21.8
Space construction equipment	0.001
Maintenance	0.8
	99.9

shown in Fig. 2. Table 3 requires careful discussion, as it embodies some of the inevitable ambiguity of net energy analysis. Column 2 shows the ER with the fuel energy included in the denominator. For this reason, all fossil fuel electric plants must have an ER with fuel of less than 1. Only a technology using a (free) renewable source can have an ER with fuel of greater than 1, as does the SPS. If the purpose is to produce electricity with a minimum of fossil fuel input, the SPS does a better job than the coal and nuclear examples listed. To be comprehensive, of course, the ER with fuel should be shown for other solar technologies. However, we do not yet have satisfactory results for other solar technologies. Calculating the ER with the fuel included



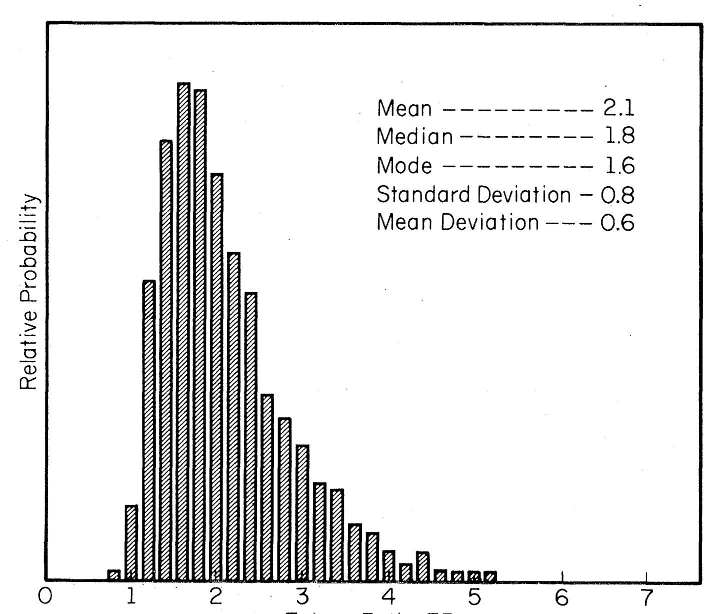


Fig. 1 (left). Schematic of Solar Power Satellite system. Circled numbers refer to modules used for energy analysis. Fig. 2 (right). Result of Monte Carlo simulation (5000 runs) of the energy ratio (ER). The height of the bars indicates the relative probability that ER is within the given interval (width = 0.2). The data shown here represent 99.9 percent of the runs, the remainder being lost in rounding. For the 5000 runs, the minimum value of ER was 0.7; the maximum, 6.6.

is equivalent to obtaining an overall, long-term, efficiency of nonrenewable energy use.

A more common view is to think of an energy technology as borrowing a certain amount of energy from the economy to produce its capital equipment, maintain its operations, and to extract its fuel, after which it pays energy back over its lifetime. If the payback energy exceeds that borrowed, the technology is said to be a source, to have an energy ratio exceeding unity. We can express the potential of a technology to pay back more than it borrows by calculating the ER without the fuel energy in the denominator. This parallels the conventional economic view of considering resources as free except for their development costs; it is a short-term view. This is done in column 3 of Table 3.

We find that the ER for the SPS is of order 2. The median of the frequency distribution in Fig. 2. is 1.8 and the standard deviation is 0.8. For comparison with conventional technologies, the choice of which definition of the ER to use thus depends on one's personal viewpoint. It seems to us that use of the ER without fuel corresponds best to the present decision criterion. Viewed in this way, the SPS seems no better—in fact, worse—than conventional technologies, which in Table 3 have ER's without fuel of 5 or more.

The relative contributions of the six modules in Table 1 and of maintenance to the total energy requirements are given in Table 4.

We note that we have not attempted here to perform a dynamic analysis—that is, to calculate the effects of a program of constructing many SPS's. Some scenarios already mentioned refer to the construction of up to 112 10-GW SPS's over 30 years, an average of four per year. We point out, however, that the dynamic problem is exacerbated by a lower ER, other things being equal.

It does seem, therefore, that the SPS is a net energy producer (*22*), although it is closer to the limit than are "conventional" technologies. A detailed comparison with terrestrial solar technologies remains to be done. We also note that the specification of the SPS is still sufficiently uncertain that this energy analysis must be viewed as relatively speculative.

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18. For all variables a truncated Gaussian was used. The Gaussian was such that, before truncation, $P = .90$ that a chosen value would fall within the range given in Table 1. If the randomly chosen value fell outside this range, it was discarded. The difference between using a truncated and using an untruncated Gaussian had little effect on the mode, median, and mean deviation, but had some effect on the mean and standard deviation.
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22. This conclusion will, of course, be strengthened if the electrical output of the SPS is multiplied by a factor of 3 to 4 to convert the electricity to a fossile fuel equivalent. We have not done so here.
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25. These percentages are the median values of the 5000-run Monte Carlo simulation.

26. M. Gibson was involved intimately in the early stages of this work but, because of other commitments, was not a participant in the final analysis. The Monte Carlo computation was performed by R. Illyes.