

Reinventing the Solar Power Satellite

Geoffrey A. Landis
Glenn Research Center, Cleveland, Ohio

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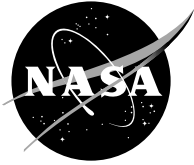
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Geoffrey A. Landis
Glenn Research Center, Cleveland, Ohio

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Geoffrey A. Landis¹
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135
E-mail: geoffrey.landis@grc.nasa.gov

Abstract

The selling price of electrical power varies with time. The economic viability of space solar power is maximum if the power can be sold at peak power rates, instead of baseline rate. Price and demand of electricity was examined from spot-market data from four example markets: New England, New York City, suburban New York, and California. The data was averaged to show the average price and demand for power as a function of time of day and time of year. Demand varies roughly by a factor of two between the early-morning minimum demand, and the afternoon maximum; both the amount of peak power, and the location of the peak, depends significantly on the location and the weather. The demand curves were compared to the availability curves for solar energy and for tracking and non-tracking satellite solar power systems, in order to compare the market value of terrestrial and solar electrical power.

In part 2, new designs for a space solar power (SSP) system were analyzed to provide electrical power to Earth for economically competitive rates. The approach was to look at innovative power architectures to more practical approaches to space solar power. A significant barrier is the initial investment required before the first power is returned. Three new concepts for solar power satellites were invented and analyzed: a solar power satellite in the Earth-Sun L2 point, a geosynchronous no-moving parts solar power satellite, and a nontracking geosynchronous solar power satellite with integral phased array. The integral-array satellite had several advantages, including an initial investment cost approximately eight times lower than the conventional design.

¹This work was presented at the 53rd International Astronautical Congress/World Space Congress, Houston TX, Oct. 10–19, 2002, as paper IAC–02–R.3.06, “Peak Power Markets for Satellite Solar Power,” and paper IAC–02–R.1.07, “Reinventing the Solar Power Satellite.”

Part 1.—Peak Power Markets for Satellite Solar Power

IAC-02-R.3.06

Abstract

The selling price of electrical power varies with time. The economic viability of space solar power is maximum if the power can be sold at peak power rates, instead of baseline rate. Price and demand of electricity was examined from spot-market data from four example markets: New England, New York City, suburban New York, and California. The data was averaged to show the average price and demand for power as a function of time of day and time of year. Demand varies roughly by a factor of two between the early-morning minimum demand, and the afternoon maximum; both the amount of peak power, and the location of the peak, depends significantly on the location and the weather. The demand curves were compared to the availability curves for solar energy and for tracking and non-tracking satellite solar power systems, in order to compare the market value of terrestrial and solar electrical power.

Introduction

The Solar Power Satellite (or "Space Solar Power," SPS) is a concept to collect solar power in space, and then transport it to the surface of the Earth by microwave (or possibly laser) beam, where it is converted into electrical power for terrestrial use [1]. The recent prominence of possible climate change due to the "greenhouse effect" from burning of fossil fuels has again brought alternative energy sources to public attention, and the time is certainly appropriate to reexamine the economics of SPS.

In the analysis of the economics of solar power satellites to provide electric power for terrestrial use, past analyses have typically assumed an averaged (or "baseline") power pricing structure. In the real world, price varies with location, season, and time of day; and the initial markets for satellite solar electricity need to be selected to maximize revenue. It is important to design the system to service the real-world electrical power market, not to an unreal average-price model. The following criteria will have to be used for a credible analysis of solar power satellite economic benefits and rate of return:

- Satellite power generation should fit electrical demand profile
- Satellite power generation should generate power at the maximum selling price
- Use actual data on electrical demand & price

Demand and Cost

Electrical Power Demand

While international and third-world markets for electricity are significant (and rising third-world power needs may eventually be the driving force for development of satellite solar power) data on price and demand is most easily available for the U.S., where a spot market for electrical power exists. Figures 1–4 show data on electrical power demand and price for urban and suburban New York and for the Boston area [2].

Figure 1 graphs the average electrical power demand versus time of day, showing the total demand from ten selected utilities serving New York City, Long Island, and some of the surrounding communities. (This graph averages demand across several days in May and June 2000). The period of high demand is seen to run from approximately 9 AM to 9 PM, when people are awake and using power, and when industrial use is maximum.

For many U.S. markets, peak power usage comes in the summer, when air-conditioning loads are high. Figure 2 shows demand data as a function of time of day from the New England ISO, serving the Boston area. This data compares June 16, a day when the outdoor temperature was high, with June 19, a comparatively cool day.

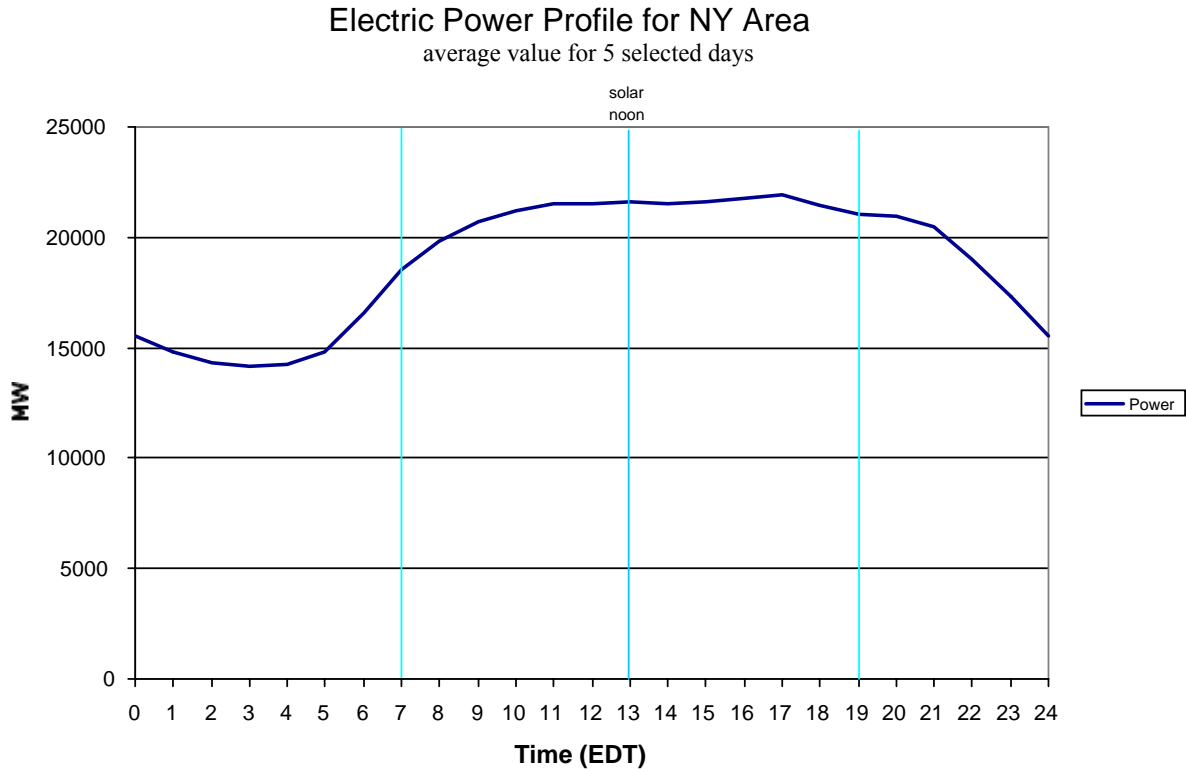


Figure 1. Power demand in MW for New York and Long Island (sum of power production from ten utilities) as a function of time of day (summer 2000 data).

Electric Demand (MW-hr)
 New England ISO
 June 16 (hot day) and June 19 (cool day)

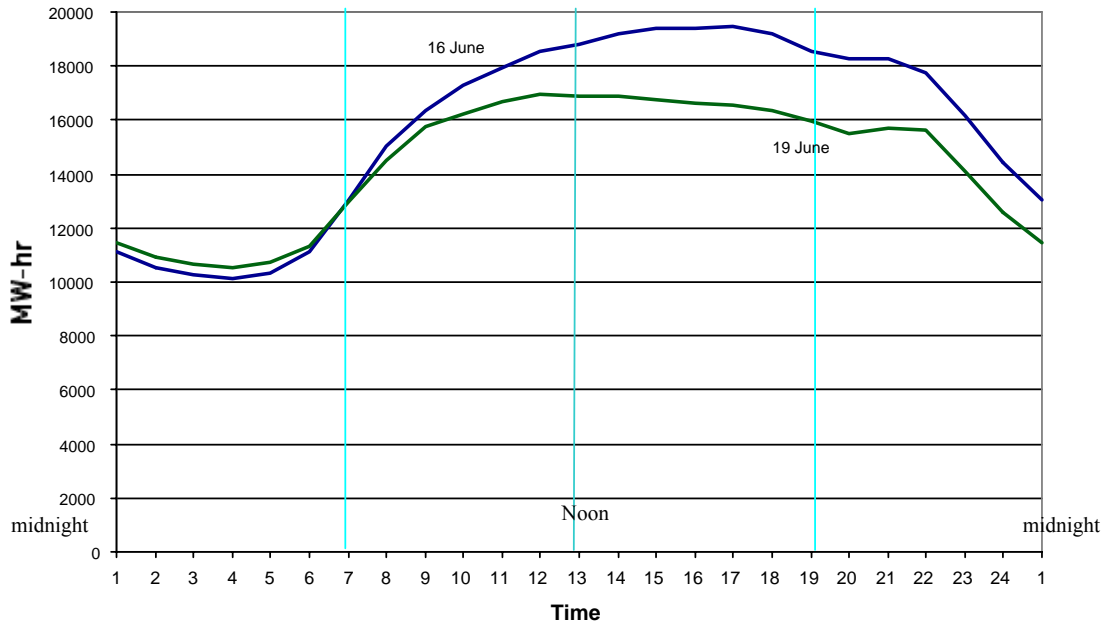


Figure 2. Electric power demand in New England, comparing a cool summer day (lower curve) with a hot summer day (upper curve). Time is Daylight Savings Time.

The difference between the power required for these two days illustrates the role of air conditioning loads in the peak power demand. The high demand period is skewed toward the afternoon, particularly during the hot day, and runs from about 8 AM to 11 PM. A secondary evening peak, representing home use of electricity for cooking, television, and so forth, is also visible.

Published data from southern California [3] shows the same trends, with the summertime demand fluctuating by roughly a factor of two between day and night. The night demand is approximately the same in winter and summer, but the daytime demand is higher in the summer, peaking in the early afternoon. In the winter, the afternoon peak vanishes, and a smaller peak at 6 to 7 PM (presumably due to electric stoves and ovens) is the highest power use.

These data are representative of region where the highest electrical use is in the summer; it should also be noted that in some markets (e.g., Florida), the maximum power demand comes in winter, when electrical heaters are used.

Electrical Power Cost

The cost (i.e., the market price of electricity to the distribution utility) follows the demand. When the demand is low, then the lowest-cost generators are used, generating continuous baseline power. At high-demand periods, higher-cost "peak power" generation is required, with spinning reserve needed to deal with instantaneous demand spikes.

Figure 3 shows the cost of electrical power in New York City, graphed at one-hour intervals through the day for a typical day in June 2000. This is the price of electricity sold to the electric distribution

system, not the consumer price. (The actual spot market price fluctuates significantly from this, as discussed later.)

The cost can be roughly divided into two periods, a "low" cost period running from roughly midnight to 7 AM, with a cost of under one cent per kilowatt hour, and a "high" cost period running from roughly 8 AM to 8 PM, where the cost is about 4 cents per kilowatt hour. During the lowest demand period, from 1 to 6 AM, the cost is under a quarter of a cent per kilowatt-hour.

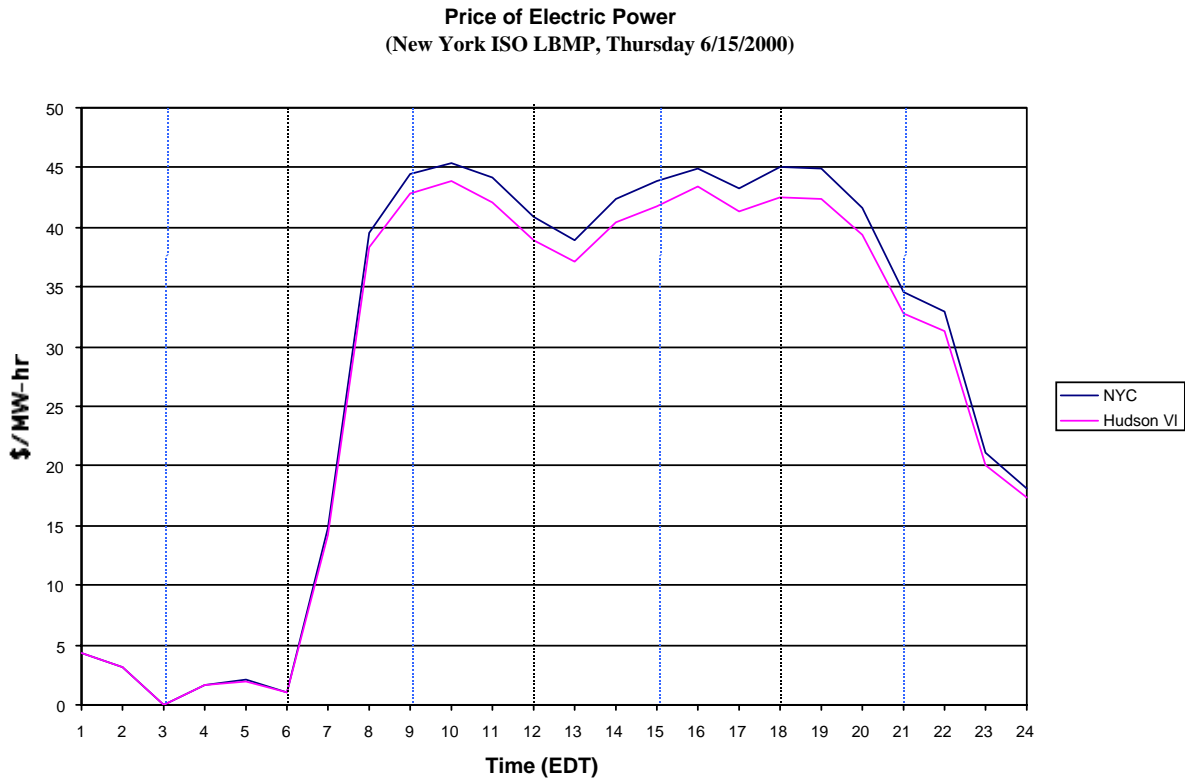


Figure 3. Power Cost (\$/MW--hr) in New York and Hudson Valley as a function of time of day.

New England Energy Cost (\$/MWh)

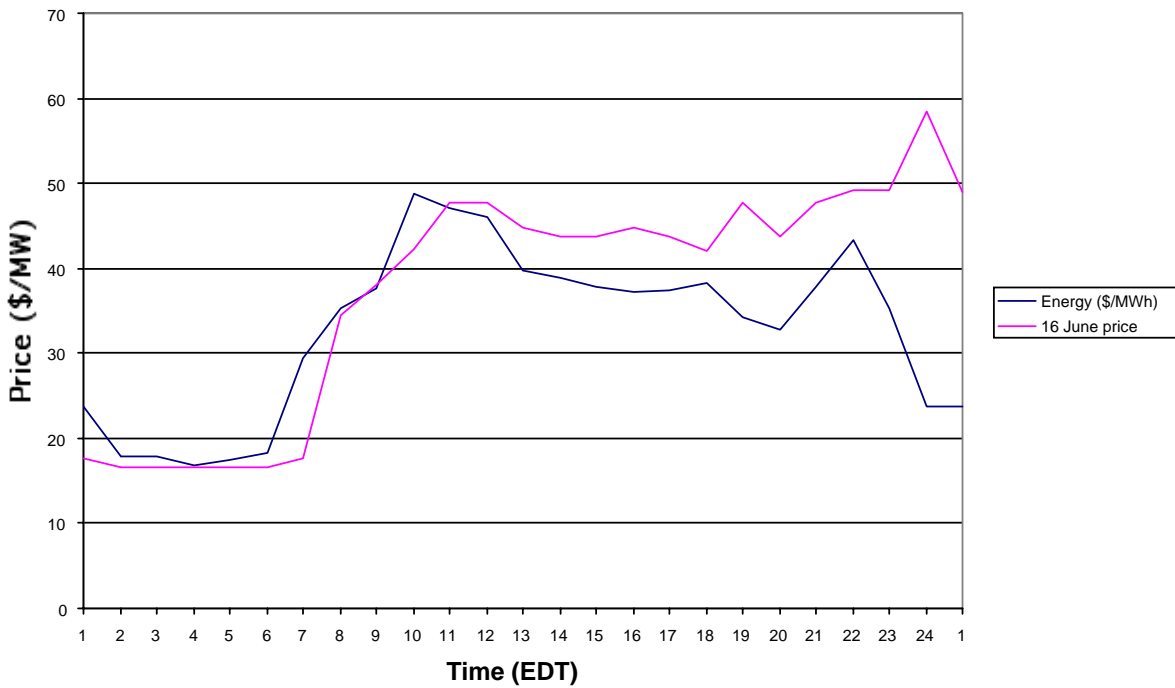


Figure 4. Power cost (\$/MW-hr) for New England, comparing a hot summer day with a cooler day.

The difference between high and low cost periods is about a factor of 4.5. The cost tracks demand: when demand is low, at night, only the low-cost baseline production is required, while when demand is high, higher-cost peaking-power supplies are brought on line to fill the demand.

Figure 4 shows cost data for New England, for the two days with demand graphed earlier. Again, there is a significant difference in the cost of power between the low usage time, 1 AM to 9 AM, and the high usage time, although the difference is only a factor of two for this service region. The cost remains high until midnight for the cooler day, and until 1 AM for the hot day.

Short-term Price Fluctuations

At high-demand periods, spinning reserve is needed to deal with instantaneous demand spikes [5]. The term "spinning reserve" comes from the fact that for short-duration demand spikes, energy stored in the rotation of the generator can be drawn.

Inadequate spinning reserve requires load shedding by the utility, with consequent loss of revenue, or else results in temporary "brown-out" conditions and loss of frequency regulation. To avoid this, electricity can be purchased on the spot market. Instantaneous spot-market electricity prices can skyrocket to very high values, an order of magnitude higher than baseload prices, due to instantaneous demand, but in general these price spikes are short lasting, and not easily predictable. To avoid these spikes, the data shown earlier was averaged.

Figure 5 shows the hourly fluctuation of the actual price to the utility for seven different days. As is shown, over this period the instantaneous price paid by the utility briefly hit spikes of over 14 cents per kilowatt-hour, considerably higher than the 4 cents per kilowatt-hour average for the high demand period.

The timing of the price fluctuations are not correlated from day to day, although they only occur during the high-demand period, since the reserve is high during the low demand period. This instantaneous price can, for brief periods, be as high as ten times the average, or occasionally even higher.

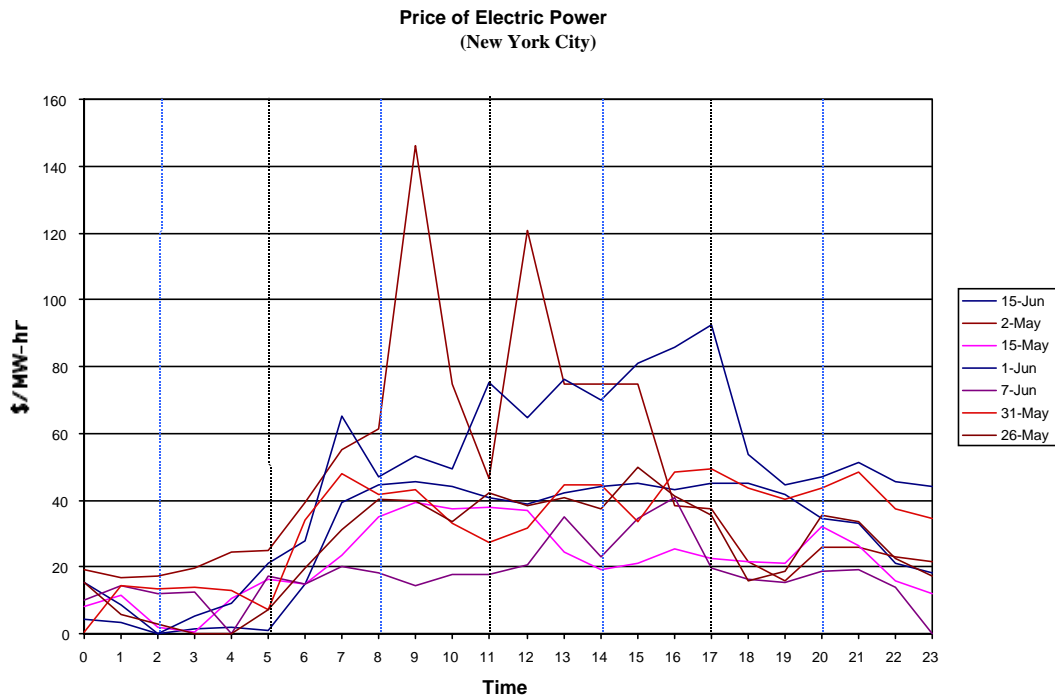


Figure 5. Short-term price fluctuations in the New York market.

Analysis

It is clear from these figures that, although conventional designs for a solar power satellite will produce a constant amount of power independent of the demand, the actual demand for electricity varies with time of day and with the day of the year, and hence the price that electrical power can be sold for varies as well, by an amount that varies from roughly a factor of two to over a factor of four, depending on market.

The conventional solar power satellite design tracks the sun, and provides continuous power, except for a period near the spring and autumnal equinox, when it is eclipsed by the Earth around midnight.

Since a solar power satellite beams power long distances, would it be possible to use a single power satellite to provide power to two different geographical markets that are substantially separated in longitude (and hence buy peak-rate power at different times)? This would be the power-beaming equivalent of "wheeling" power from one geographic location to another.

Since the peak price period lasts nearly twelve hours (e.g., 8 AM to 8 PM for New York), for a single satellite to provide power to two separate markets at peak rates for both markets would require the two markets be at longitudes separated by nearly 180 degrees. If the downlink power beam is allowed to reach the Earth at 90-degree incident angle (i.e., from a satellite on the horizon), then a single geosynchronous satellite could service two sites on the equator separated by no more than 162 degrees of longitude.

In reality, grazing-incidence is not practical. (Among other things, it would require a vertically-oriented rectenna.)

For a more practical case, assume that the maximum allowable zenith angle is 45 degrees. In this case two locations served by the same geosynchronous orbit solar power satellite can be at most 80 degrees (5.3 hours) apart. This geometry is shown in figure 6 (top). The maximum separation is lower if the sites are not on the equator.

This would be sufficient separation to extend the period over which the satellite is providing high-price power from roughly 12 hours per day to roughly 17 hours per day.

Note that in this case, the ground infrastructure of rectenna, land, and distribution system is doubled. This trade-off is only reasonable if the ground infrastructure cost is not the major fraction of the power cost.

If the beam could be diverted through a relay satellite (figure 6, bottom), then larger separations could be achieved; in principle up to the most desirable case of a 180 degree separation. (In the geometry shown in figure 6, where the relay satellite is in a lower orbit than the beaming satellite, several relay satellites would be required to provide continuous coverage; each relay satellite, however, can sequentially service several markets.) Although a power relay satellite in principle is just a passive microwave mirror, in practice it will have to contain tracking, guidance, and orbit maintenance avionics of a sophistication equal or greater that of the solar power satellite. If the cost is a substantial fraction of the cost of the solar power satellite itself, then it makes more sense to simply build a second SPS, rather than the relay satellites.

While it is not currently clear that a power relay satellite will be enough lower in cost to make servicing two markets with a power relay practical, the fact that this would allow power to be sold at high price during a period when otherwise the satellite would be selling power at low price means that this concept deserves study.

Servicing the Spot Market

Even higher revenue could be achieved if the solar power satellite could service the spot market, where instantaneous price of electricity can, for brief periods, rise to an order of magnitude higher than the peak-power cost. This would require a power satellite with the ability to switch beams from one ground location to a different ground location rapidly (within a few tens of seconds). Since instant spot demands are short, such a satellite would have to serve perhaps ten different utilities or more to average enough high-price demand markets; the cost of the ground infrastructure may make this prohibitive.

A satellite which serves the short-term spot market cannot, between high-price spikes, sell power at peak power rates, since the ability to command premium rates is contingent on reliability of power supply. If the power is taken offline to service a peak demand elsewhere, the service cannot be relied on, and hence cannot sell for premium rates; conversely if the power is supplied to a utility at peak-power rates, the beam cannot be momentarily diverted to service a utility with a temporary demand spike.

There is probably not enough money represented by the brief high-price spikes to make this concept worthwhile in light of the cost of replicating the ground infrastructure over ten or more sites, but if the ground infrastructure is low enough in cost, it may be worthwhile.

Fixed orientation SPS

Since power during the peak period is priced at nearly twice the average price, and power at the off-peak is nearly valueless, it is worth considering whether it might be possible to simplify the power satellite design by eliminating the tracking. A flat-plate, non tracking solar array will produce only $1/\pi$ as much power as a tracking satellite, but in principle could be directed to produce that power at the most optimum period of the day, when the value of the power is roughly double the average value. If the reduction in cost due to the gain in simplicity of such a satellite is large, this might be a worthwhile trade.

Figure 7 shows, as an example, the power produced by such a fixed orientation solar power satellite, compared with the power demand of New York from figure 1. In this graph, the peak amount of power produced has been scaled so that at the maximum power production by the satellite, the generation capacity not met by the space solar power system does not fall below the lowest value during the daytime.

In the example, this would result in reducing the maximum amount of power produced by the utilities by 850 MW, representing a peak-shaving to the utilities of 4%. Higher power production from the satellite would result in the peak power production at solar noon overfilling the peak demand, and thus, since the (non-solar) production at noon is lower than the lowest night value, the solar power satellite will be selling at minimum price, rather than maximum.

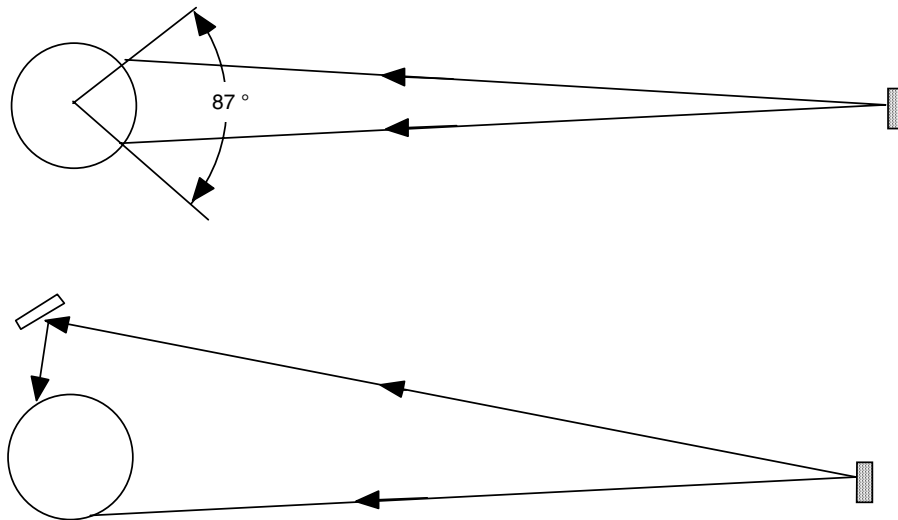


Figure 6. A single solar power satellite can service two markets on the Earth either directly (top) or by a relay satellite (bottom).

Comparison of NYC Area Electric Power Requirement to 7.5 GW(peak) Solar installation output

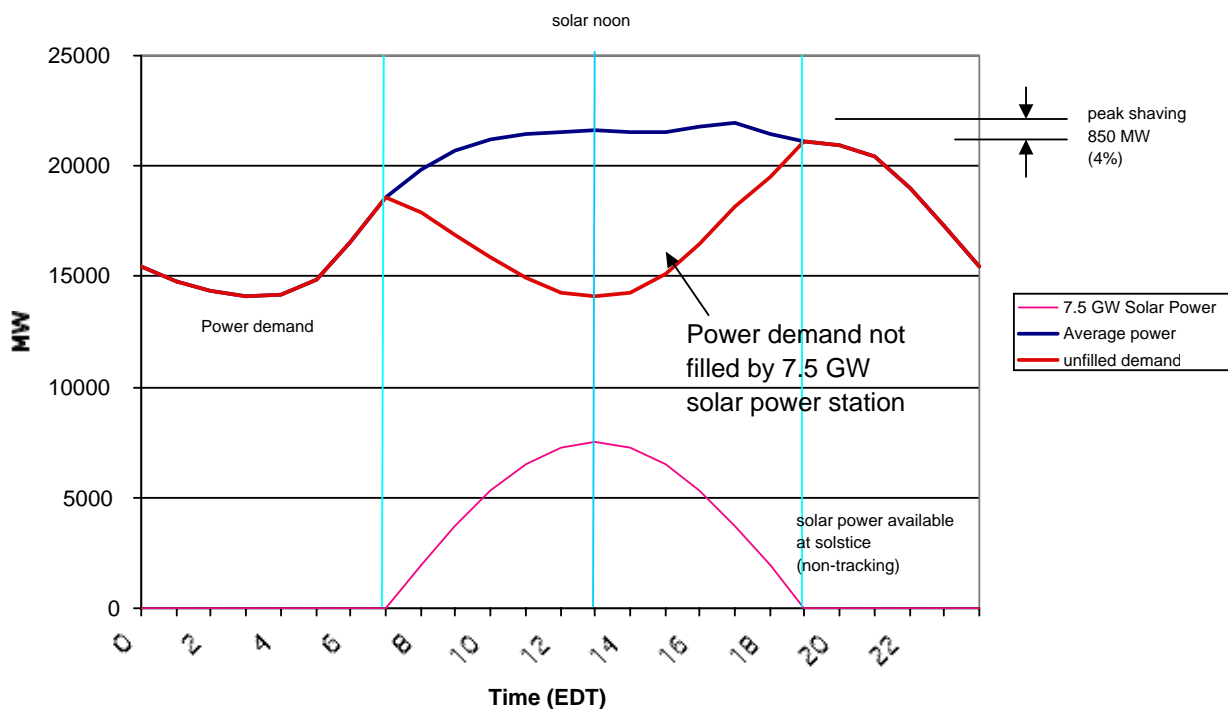


Figure 7. Power Demand for New York, showing a 6.5GW(peak) solar power station used for peak-shaving.

Synergy With Terrestrial Solar

Space and Ground Solar Power

Analyses of space solar power often assume that ground solar power is a competing technology, and show that space solar power is a preferable technology on a rate of return basis. In fact, however, space solar power and ground solar power are complementary technologies, not competing technologies. These considerations were initially discussed in 1990 [4]. Low-cost ground solar power is a necessary precursor to space solar power: Space solar power requires low cost, high production and high efficiency solar arrays, and these technologies will make ground solar attractive for many markets. The ground solar power market, in turn, will serve develop technology and the high-volume production readiness for space solar power.

Since ground solar is a necessary precursor to space solar power, an analysis of space solar power should consider how it interfaces with the ground-based solar infrastructure that will be developing on a faster scale than the space infrastructure. Some possible ways that this interface could be optimized include:

1. Integrate solar and microwave receivers on ground. This will allow the space solar power to use the pre-existing land that has already been amortized by ground solar power receivers, and tie in to power conditioning and distribution networks that are already in place.

2. Use solar power satellites to beam to receivers when ground solar is unavailable. By "filling in" power when ground solar is unavailable, space solar power will serve as the complement to solar. This requires an analysis of the match between solar availability, power demand, and power availability from space.

So in addition to the five requirements for economic analysis given earlier, a desirable additional requirement is:

- Analyze the space solar power system keeping in mind that it must complement the ground solar infrastructure.

Satellite Power for Night Supplement

In 1997, Landis proposed to locate a solar power satellite at the Earth-sun L2 Lagrange point, where it has a constant view of the night side of the Earth [6,7]. The proposed benefit of this location would be that the satellite could supplement daytime ground solar power by providing night power. From the demand graphs, however, it is clear that this approach would result in power supplied during the low demand (and hence low price) portion of the day.

If in the future ground solar generation becomes a large fraction of the electric supply of the Earth, the price curve will shift to make this the high-price period. However, it is unlikely that this system design would be economically favorable in the near term.

Demand With Ground Solar Supplement

Figure 6 compares the power required for New York with the power produced by a fixed solar plant designed to supply power during this daytime peak. This power production is now envisioned as a ground-based 7.5 GW solar field, tilted slightly to the west to shift the peak to 2 PM (i.e., 1 hour after solar noon, including daylight savings correction). The ground solar installation produces power almost entirely during the peak cost time.

The demand not filled by ground solar now is a two-peaked distribution, instead of a single peaked power distribution.

A design to produce power to optimally fit the two-peak distribution shown might be a fixed, two sided array. The simplest version of such a solar power satellite geometry [7] is shown in figure 8.

In this power satellite concept the 6 AM/6 PM timing of the power peaks is not optimally matched to the demand curve, even after the solar production is subtracted, since much of the power is produced too early or too late in the day. A better match could be achieved if the two arrays are tilted relative to each other, in a "V" configuration. This is shown in figure 9.

As the power produced by the solar power satellite grows, and eventually supplants the ground solar, the two-panel system shown in figure 9 can be optimized to supply the peaking loads.

Figure 10 shows the output from a V-shaped solar power satellite optimized to supply the peak-power loads of New York City. As is clear from the graph, the power production profile is much smoother after the solar power satellite's contribution fills in the peak power.

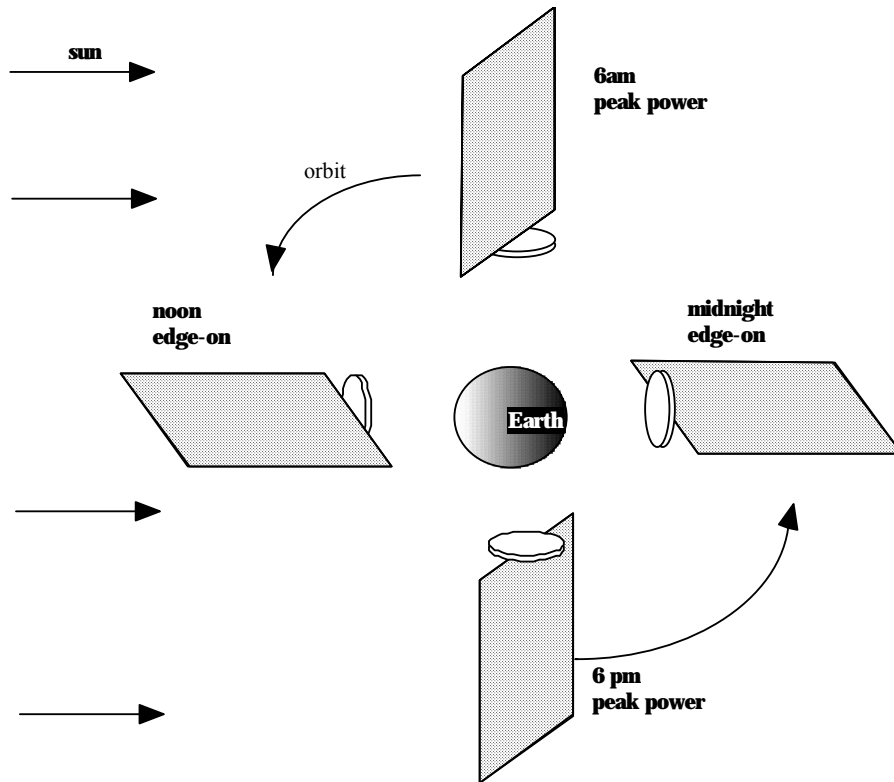


Figure 8. Fixed two-sided solar array to provide fill-in power to a ground solar installation [7].

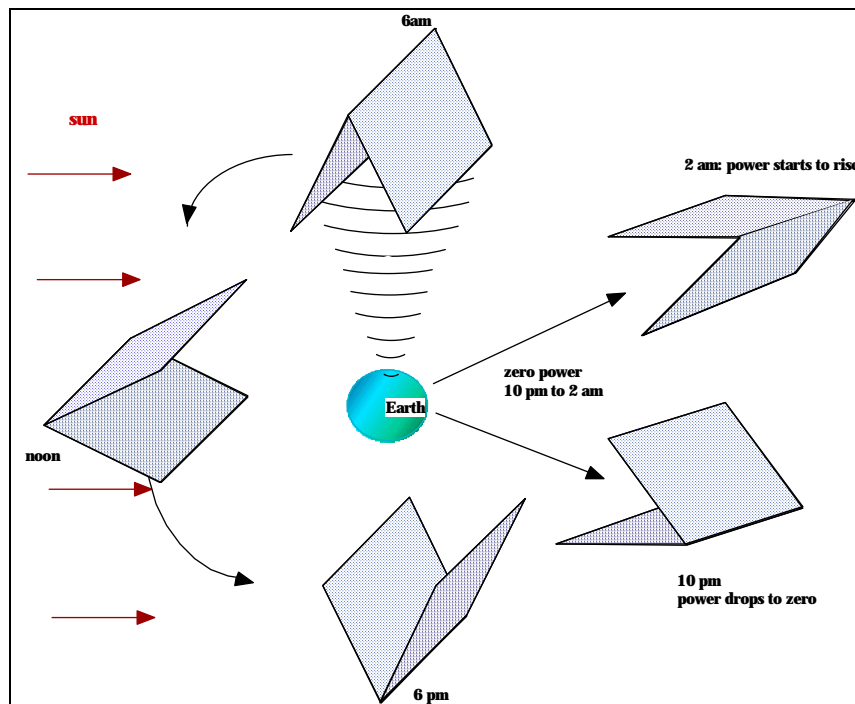
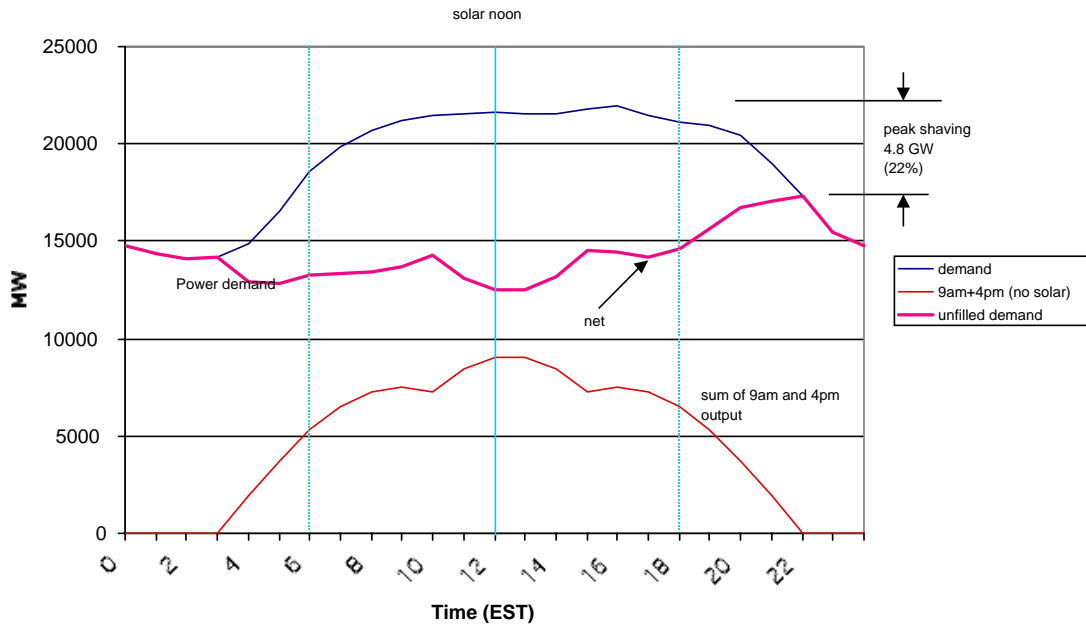


Figure 9. V-shaped fixed orientation solar power satellite to provide fill-in power for a ground solar installation [7].

Comparison of NYC Area Electric Power Requirement to 7.5 GW(peak) 9am/4pm SPS output



Conclusions

The economic case for a solar power satellite is most compelling if the solar power satellite can generate power that sells at peak, rather than average, price. Data from New York and Boston were examined to determine when the peak power prices occur. Several new designs for solar power satellites were considered, in an attempt to maximize the amount of power produced at peak rates.

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Part 2.—Reinventing the Solar Power Satellite

IAC-02-R.1.07

Introduction

Background

Space solar power is potentially an enormous business. Current world electrical consumption represents a value at the consumer level of nearly a trillion dollars per year; clearly even if only a small fraction of this market can be tapped by space solar power systems, the amount of revenue that could be produced is staggering.

To tap this potential market, it is necessary that a solar power satellite concept has the potential to be technically and economically practical. Technical feasibility requires that the concept not violate fundamental laws of physics, that it not require technology not likely to be developed in the time frame of interest, and that it has no technological show-stoppers. Economic feasibility requires that the system can be produced at a cost which is lower than the market value for the product, with an initial investment low enough to attract investors, and that it serve a market niche that is able to pay.

The baseline "power tower" developed by the "Fresh Look" study in 1996 and 1997 [1,2,7] only partially satisfies these criteria. One difficulty is the power distribution system. The distribution system required to transfer power from the solar arrays to the microwave transmitters, consisting of a long high-voltage tether system, can not operate in the environment of near-Earth space at the voltages required without short-circuiting to the space plasma. Lowering the voltage to avoid plasma discharge would result in unacceptable resistive losses.

Power distribution is a general problem with all conventional solar power system designs: as a design scales up to high power levels, the mass of wire required to link the power generation system to the microwave transmitter becomes a showstopper. A design is required in which the solar power can be used directly at the solar array, rather than being sent over wires to a separate transmitter. (The "solar sandwich" design of the late 70's solved this problem, but only with the addition of an unwieldy steering mirror, which complicates the design to an impractical extent).

In addition to technical difficulties, the baseline concept does not meet economic goals. As shown in table 6-4 of the "Fresh Look" final report [1], even with extremely optimistic assumptions of system cost, solar cell efficiency, and launch cost, each design analyzed results in a cost which is either immediately too expensive, or else yields a cost marginally competitive (but not significantly better) than terrestrial power technologies, with an internal rate of return (IRR) too low for investment to make money. Only if an "externality surcharge" is added to non-space power sources to account for the economic impact of fossil-fuels did space solar power options make economic sense. While "externality" factors are quite real, and represent a true cost impact of fossil-fuel generation, it is unlikely that the world community will artificially impose such charges merely to make space solar power economically feasible.

The value of the solar power concept, however—both the dollar value and the potential value of the ecological benefits—is so great that the concept should not be abandoned simply because one candidate system is flawed. It is important to analyze alternative concepts in order to find one that presents a workable system.

At the technical interchange meeting which kicked off the "Fresh Look" study of solar power satellites in 1995, innovative concepts for solar power satellites were solicited in the "brainstorming" sessions [1,2,8]. However, none of the new concepts were developed in detail.

1 Space Power Markets

There are a large number of potential markets for space solar power. The greatest need for new power is in the industrializing third world; unfortunately, this market segment is by most analyses the least able to pay.

Possibly the most interesting market is third-world "Mega-cities," where a "Mega-city" is defined as a city with population of over ten million, such as São Paolo, Mexico City, Shanghai, or Jakarta. By 2020 there are predicted to be 26 mega-cities in the world, primarily in the third world; the population shift in the third world from rural to urban has been adding one to two more cities to this category every year, with the trend accelerating. Even though, in general, the third world is not able to pay high prices for energy, the current power cost in mega-cities is very high, since the power sources are inadequate, and the number of consumers is large. Since the required power for such cities is very high-- ten billion watts or higher-- they represent an attractive market for satellite power systems, which scale best at high power levels since the transmitter and receiver array sizes are fixed by geometry. In the future, there will be markets for power systems at enormous scales to feed these mega-city markets. Therefore, it is very attractive to look at the mega-city market as a candidate market for satellite power systems.

For more near-term economic feasibility, however, it is desirable to look at electricity markets within the United States. The economic climate of the United States is more likely to allow possible investment in large-scale electric power projects than the poorer "developing" nations, and hence it is more likely that the first satellite-power projects will be built to service the electrical market in the U.S. Although in the long term the third-world mega-cities may be the region that has the greatest growth in electrical power demand, the initial economic feasibility of a space solar project will depend on the ability of such a facility to be competitive in the U.S. electric market.

2 Terrestrial Solar Power

An economic criticism of satellite solar power systems is that when the solar array price is low enough to make satellite solar power economically feasible (typically on the order of \$0.50 per watt of array), it makes more economic sense to generate the power using the solar arrays on the Earth. At the array prices required, space solar power systems will compete against very cheap terrestrial solar power, not against current-technology prices.

It makes sense to develop space solar power in a way so as to make it synergetic with ground-based solar power [4]. The terrestrial solar power market will ramp-up the solar array production to the levels required for space solar power anyway; why can't we find a space solar power concept that can take advantage of the ground solar power capacity that will be installed and operational long before the first satellite power station can turn on?

Table 1 shows the advantages of using space solar as a "plug and play" replacement for ground solar arrays. From the point of view of a utility customer, a rectenna to receive space-solar power looks just like a ground solar array-- both of them take energy beamed from outer space (in the form of light for solar power, in the form of microwaves for the space solar power) and turn it into DC electricity. If the space solar receivers are set up in the same place as the ground solar arrays-- in the best case, if the same arrays can be used for both-- the market for the space solar power is pre-sold. SSP becomes a drop-in replacement for an existing product, with the added advantage that it works at night.

Table 1

A Natural Synergy: Ground-based solar as the precursor to space solar power

Ground solar precedes space solar

1. Ground solar economically feasible in good locations as soon as solar array price reaches SSP targets
2. Does not need to wait for development of the beaming technology or low-cost space transportation

Upgrade ground-solar facilities to space solar

- 1. SPS receiver looks and operates just like a solar array**
 - A. Both receive power from space and converts it to electricity
 - B. Utilities see “plug and play” replacement that operates at night
- 2. SPS rectennas can be put at the same location as solar facility**
 - rectenna sites bought and paid for by ground solar
 - energy distribution infrastructure already in place
 - rectennas can be made transparent to sunlight
 - or advanced solar array can be designed with integral rectenna built in

Approach:

- Design a SPS to capitalize on the synergy between ground solar and space solar [4,14].
- Such a satellite concept must use ground-based solar when it is economical to do so, but fill in for ground-based solar when ground based solar is inadequate.

3 Supersynchronous Solar Power Satellite

Rather than the MEO and GEO orbits discussed in the earlier study, it is proposed here to analyze a solar power satellite put into a completely different orbit, the Earth-sun L-2 halo orbit. This concept for a space solar power satellite is originally proposed in the paper "A Supersynchronous Solar Power Satellite" [3].

The location of the Earth-sun L2, and a typical halo orbit around it, are shown in figure 1. This is referred to as a "supersynchronous" location for a solar power satellite, since it is located beyond synchronous orbit. While the halo orbits around the lagrangian points are slightly unstable, the instability is so weak that several space probes have used the L1 halo orbit for operational use, with only minimal amounts of propellant needed to keep them in position.

At first consideration, it would seem that the Earth-sun L2 point is a poor choice for a space solar power system transmitter. At a distance of point 1.5 million kilometers from the Earth, it will be forty times further away from the Earth than a satellite placed in geosynchronous orbit. However, it turns out that this orbit allows design simplifications to the satellite solar power design that more than compensate for this disadvantage.

First, by being located further from the sun than the Earth, the satellite beams continuously to the night side of the Earth. Thus, it is perfectly suited to fill in night power to solar arrays which receive solar power during the daytime. This allows a ground-based solar array field to be "upgraded" to a 24-hour power source, and hence, by upgrading the status of the power from "intermittent" to "baseload," increases the selling price of the power from low intermittent power levels, to higher baseload power levels. The satellite power system becomes an upgrade to an existing power system, with the consequent advantages listed in table 1.

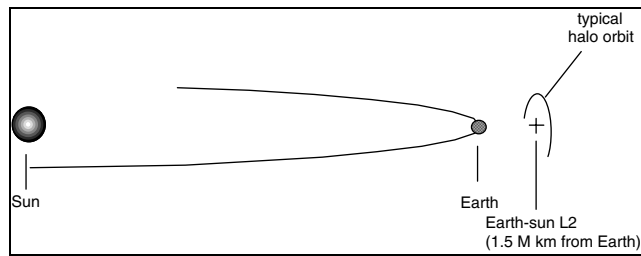


Figure 1. The Earth-sun L2 point, and an example of a typical halo orbit around it.

The system will beam to three power receivers sequentially, shifting the beam slightly as one rotates out of the line of sight and the new one rotates into line of sight. (For example, three third-world cities of over ten million population located roughly 120° around the globe are Mexico, Cairo, and Shanghai. Each of these cities is power-starved, with expensive, unreliable electrical power and frequent brown-outs on the power system, and each of these governments has publicly pledged to erect large-scale fossil-fuel power plants to service the growing needs of their burgeoning population.)

By use of a halo orbit, the power system transmitter can be put in a spot where it does not enter the Earth's shadow, and yet still has the advantage of only viewing the night side of the Earth.

The main design simplification is due to the fact that the Earth and the sun are located in the same direction. This allows the design to consist of thousands of individual elements, each separately phased and thus requiring no connection to any other element, and most particularly, requiring no system of power distribution-- the power for each element is generated locally. The design can now incorporate an integrated PV receiver/microwave transmitter dish. Each individual element can be aimed both at the sun and at the Earth, and the beams combined by phased-array techniques.

Compared to Geosynchronous SPS designs:

- Multi-gigawatt electrical cabling eliminated
- Entire system is at low voltage; no arcing
- Rotary joint eliminated
- Rotating electrical feedthrough eliminated
- Microwave dish doubles as PV concentrator
- No element is critical; failure tolerant design
- Only minor beam scanning required
- Every element is exactly identical
- Mass production of elements yields low cost

This results in a much simpler design than the GEO satellite concept. Table 2 shows some of the design features for a typical design. The design requires 33,000 individual PV/Solid state amplifier units, each featuring an inflatable mirror which doubles as a parabolic antenna. Since each unit can be mass-produced, the cost is relatively low. Figure 2 shows an overall view of the design concept for a single element.

Figure 3 shows a front view and side view of how the elements are put together to form a transmission/receiving array. Each individual element is aimed at the receiver site at Earth, but the relatively small mirror size (compared to the transmission distance) means that the spot from a single mirror at the Earth is a relatively large size. The spot is narrowed by phasing all 33,000 individual elements to a phase selected (and actively controlled) to the rectenna target. To avoid "grating lobes," the individual elements must be closely packed in the x-y plane, and thus must be either hexagonal (as shown in figure 3) or square (with acknowledgement to R. Dickinson of JPL for elucidating this effect). Alternately, if losses due to grating lobes are acceptable, and will not illuminate the Earth with

microwaves, then the individual elements can be round. This would reduce the power by about 15% compared to the tightly packed array.

Table 2: Earth-Sun L2 Design details

The space power system designed to be located Earth-Sun L2 will be radically different from conventional GEO Space power concept

Since the sun and Earth are nearly the same direction, it can feature:

- Integrated solar concentrator dish/microwave transmission dish
- Integrated solar cell/solid state transmitters
- **No rotating parts or slip-rings**

Frequency: 30 GHz:

efficiency is lower than 2.45 GHz, but much tighter beam

- transmitter diameter: 3 km
- receiver diameter: 6 km
- 3 ground sites, receive 8 hours per day

33,000 16.5 meter integrated PV concentrator/transmitter elements

- Concentrator PV efficiency 35%

Table 3 shows mass estimates for a single concentrator element. Based on L'Garde designs for inflatable microwave antennas, it should be possible to make a 16.5-meter concentrator/antenna dish for 15 kg. The solar array/solid state power amplifier array adds an additional 9 kg, for a mass of 24 kg per element.

Figure 4 shows one concept for a full system. In this system, the beam has been "apodized" to minimize the amount of beam spill outside the target. The apodization process is done by adding rings of transmitter outside of the main circular transmitter; these rings cancel out the limbs of the gaussian pattern, allowing a tighter beam on target and also a flatter distribution of energy across the rectenna.

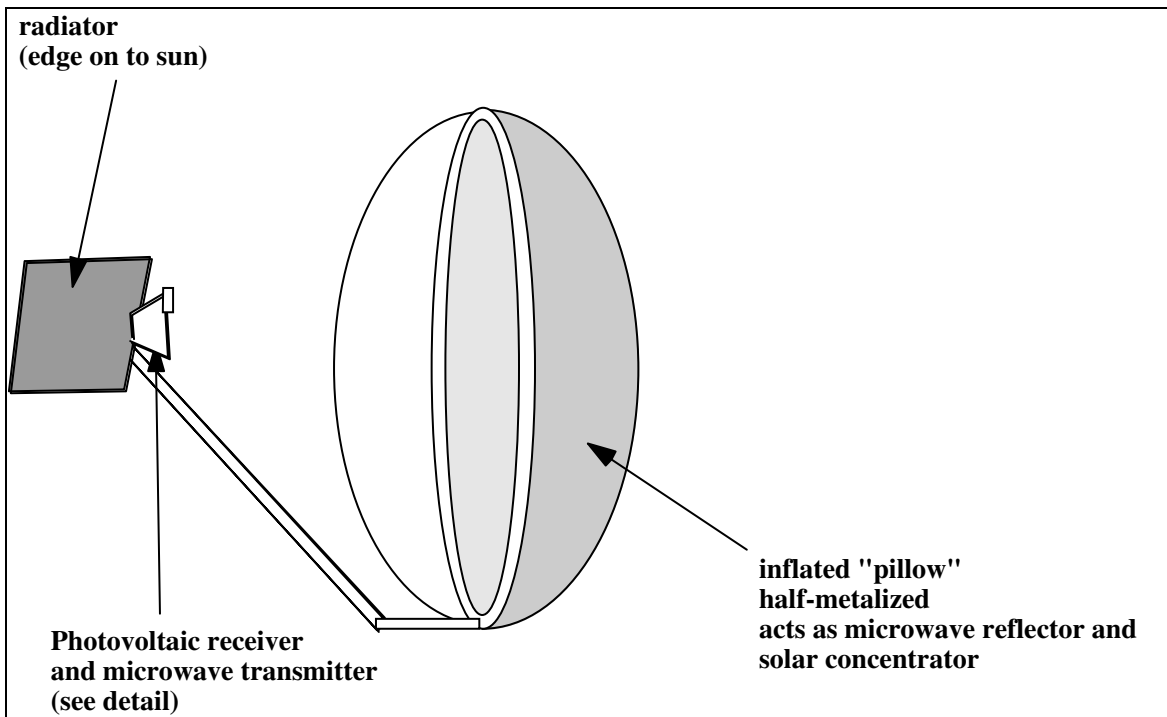


Figure 2. Individual concentrator/PV/solid-state-transmitter/parabolic reflector element.

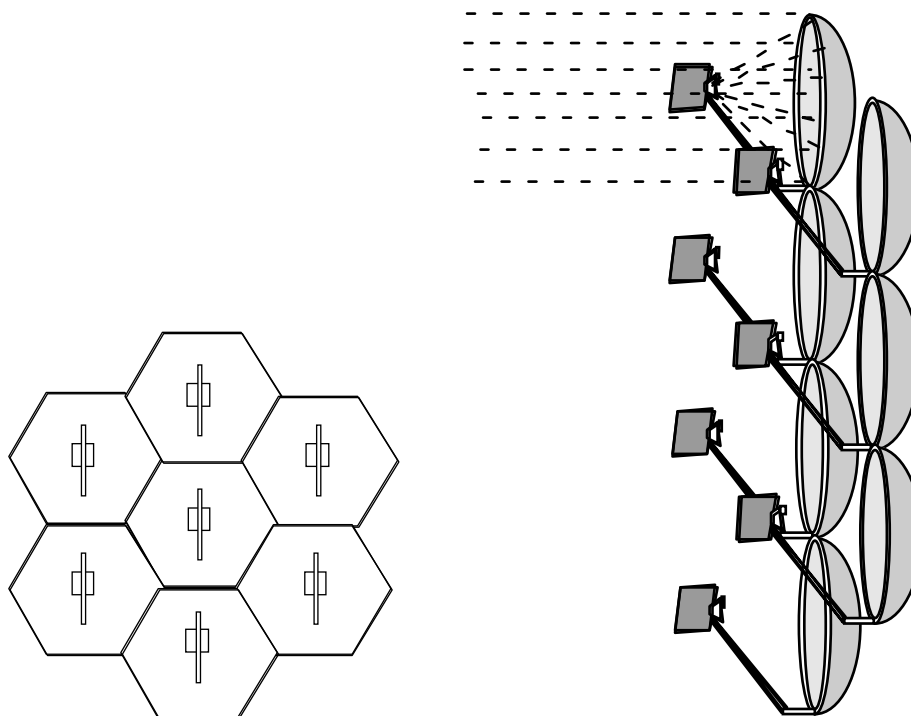


Figure 3. View of how multiple elements fit together into a single filled aperture.

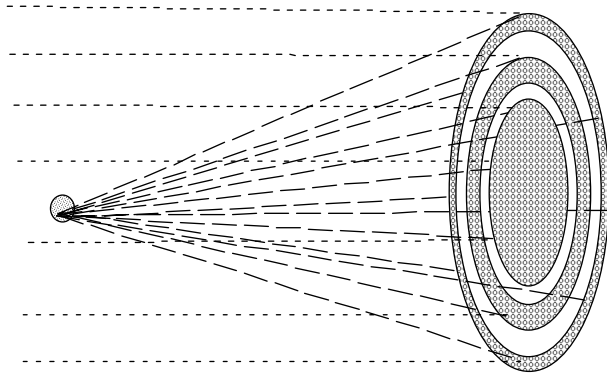


Figure 4. Apodized array beaming into Earth.

Table 3: Supersynchronous Solar Power Satellite: Mass and power

<p>Mass of mirror element <u>L'Garde estimate:</u> F/d=1 dish of diameter 16.5 meters could be built for mass of 15 kg</p> <ul style="list-style-type: none"> • Similar to the design flown on the shuttle • Solar concentration ratio 50, focal plane area 4.28 square meters • Focal plane array mass is 9 kg • total mass per dish is 24 kg • PV power per dish is 100 kW <p>Total Mass Inflatable PV concentrator/transmitter elements mass 15 kg each (L'Garde design) PV mass 9 kg each (50x concentration) <u>Structural mass 500,000 kg</u> Total Mass 1,300 tonnes At assumed transmitter efficiency 33% (today's technology): 1 GW power output At assumed transmitter efficiency 67% (future technology): 2 GW power output</p>

Although such a design is much simpler than a geosynchronous orbit satellite, the bottom line of viability for a SPS system is not simplicity, but cost.

The SPS design comprises large numbers of identical units which can be mass-produced. The design had no moving parts, and can use extremely simple pointing. The cost of the solar cells themselves is minimized by use of concentrating mirrors. The most significant cost element is the launch cost. If the launch cost can be reduced to reasonable numbers, the total space segment cost can be feasible.

4 Disadvantages of Earth-sun L2 Solar Power Satellite

There were several difficulties with the Supersynchronous Earth-sun L2 solar power satellite that make it a poor choice for a financially successful design.

1. Size. The satellite-Earth distance of 1.5 million km means that the physics of diffraction demands a large size. This means that the initial cost will be high.

2. Electrical generation profile. The design produces power primarily during the night. For the existing U.S. power market, the maximum power usage is during the day. While the demand profile may change when large amounts of ground solar power become installed, in the current electrical market, the night delivery of power results in power being sold at the lowest price.

Unfortunately, the very trait which makes the L2 solar power satellite attractive in the first place—power generation focused on the night—also makes it unattractive for initial investment.

5 Fixed Geosynchronous Solar Power Satellite

While the size and the electrical generation profile with the Earth-sun L2 solar power satellite make it a poor choice for a financially successful design, one aspect of the design remains extremely attractive: the absence of a rotary joint makes the L2 solar power satellite a design with no moving parts.

Therefore, I decided to investigate whether it would be feasible to design a solar power satellite with no moving parts in geosynchronous orbit. The baseline figure of merit for this design was to examine how the power production profile fits with the demand (and price) profile for terrestrial electrical power, assuming that the power is to "fill in" for a ground solar power system.

The satellite designed with the same design criteria: maximum simplicity; no moving parts; mission is to power when ground solar power is not available. The design was presented at the second SERT technical integration meeting [12] and analyzed in more detail at the third SERT technical integration meeting [13].

Figure 5 shows the initial concept. A fixed microwave transmitter is permanently mounted on a bifacial solar array, which can be illuminated from either side. Figures 6 and 7 shows that this concept produces maximum power dawn and at dusk, with zero power production at noon and at midnight. This fills in for a hypothetical solar array on the ground, which produces maximum power at noon and zero power at dawn and dusk.

By employing a fixed transmitter attached to the solar array, the power management and distribution system size can be greatly simplified and reduced in mass. The difficulties associated with power transfer from the array to the transmitter are minimized, and the mass and cost of the SPS are reduced. The new SPS needs only gravity-gradient stabilization to ensure that the transmitter remains pointed to the rectenna site on the Earth. The solar array is now a simple flat structure to support the photovoltaic solar cells. Since the array is designed to have cosine illumination, a complicated structure is not required to point the arrays to the Sun. Therefore further mass and cost savings may be realized.

Note that the simplified design produces power with a cosine dependence. The total power produced is therefore equal to the (absolute value of cosine theta) averaged from zero to two pi (ignoring the seasonal variation, which is a separate cosine factor of the beta angle). The average of the absolute value of cosine is $2/\pi$. Over the course of a day, the fixed array produces 64% of the energy of a tracking array of the same size.

6 Analysis Using "Space Segment Model" Spreadsheet

In 1995, NASA commissioned a study to examine the feasibility of space solar power for use on Earth. This "Fresh Look", completed in April 1997, studied new SSP concepts, architectures, and technologies. As a part of this study, Science Applications International Corporation (SAIC) developed an evaluation tool to use to compare solar power satellite designs with a common set of assumptions. This is a solar power satellite model using Microsoft Excel entitled the Space Segment Model (SSM) [10, 11]. The purpose of the SSM is to evaluate the impact of technology and design choices on the mass, performance, and cost of various solar power satellite (SPS) concepts using a common model.

The Space Segment Model is a Microsoft Excel 97 workbook consisting of 25 worksheets.

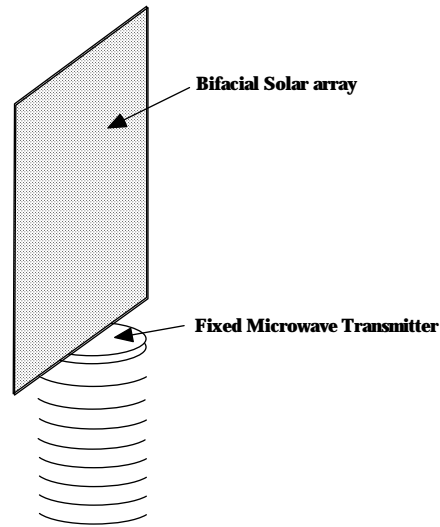


Figure 5. Solar power satellite design with fixed microwave transmitter (no moving parts).

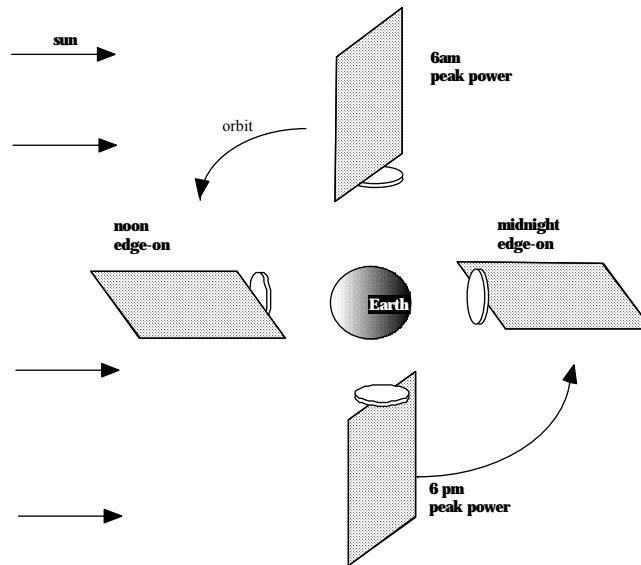


Figure 6. GEO solar power satellite provides maximum power at 6 AM and 6 PM.

In the Input worksheet, the user chooses various SPS concepts, architectures, and orbital parameters. The chosen parameters are used in the various other worksheets according to their purpose, and the relevant values are output to the summary worksheet. The user may go to each specific worksheet to examine how performance and cost characteristics are evaluated, and may make changes to these worksheets. This allows the user to customize to some degree the SSM to fit the SPS concept under study.

For the purposes of this study, the SSM provides more analysis than required. Several of the worksheet calculations were not applicable, such as market cities and interplanetary trajectory calculations. For the applicable worksheets, namely Solar Collection, Power Management and Distribution (PMAD), Power Transmission, Structure, and Propulsion, default values were used in many cases, as they were appropriate to the concept under study. When necessary, relevant values in the applicable worksheets were altered to suit the concept under study. By selectively altering the SSM, the model was used to determine the viability of the concept under study.

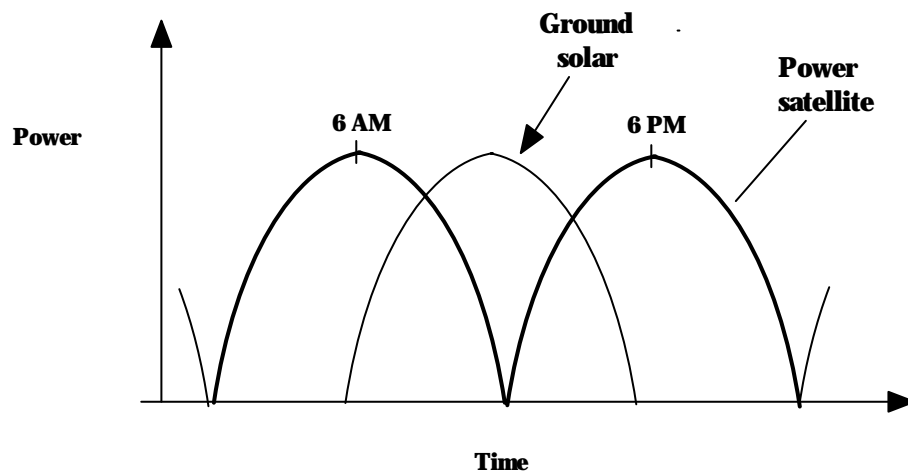


Figure 7. Power production from the fixed GEO power satellite, compared with assumed cosine dependence of ground power system.

The Space Segment Model was used to perform a first-order sizing of the concept. By inputting the desired values of SPS concept, structure type, orbit type, power delivered, photovoltaic cell type, transmitter frequency, etc results of system and subsystem mass and cost were output to the Summary worksheet. Then relevant values in the appropriate sub-system worksheets were altered to better reflect the proposed design. A standard design was compared with the fixed design.

The "Abacus" solar array structure was chosen since it resembles the 1979 Reference System structure but incorporates mass savings, and appropriate modifications could be made more readily. In effect, it applies technological developments to the 1979 Reference System structure. The design considered is a bi-facial solar array which would require two arrays with power scaled to deliver 1 GW ground power scaled accordingly with values from the Solar Conversion worksheet. Thin film solar cell arrays were assumed. Transmission frequency of 5.8 GHz was chosen. Higher frequencies suffer from unacceptable atmospheric attenuation, and lower frequencies require larger transmitter arrays and/or rectennas.

When revising the Space Segment Model to fit with the proposed concepts, each subsystem can be modified to a certain degree, and some cannot be modified at all. The differences between the baseline and the fixed GEO systems are:

Transmitter subsystem: no modification since it is identical in both cases. It is sized according to power output and frequency; other SPS variables have no effect on the transmitter.

Solar conversion subsystem: revised to be a bi-facial array, as opposed to a single sun-tracking array.

Attitude control and orbit maintenance: reduced since the fixed SPS would be gravity-gradient stabilized. While stationkeeping cannot be neglected in a thorough design, for a first-order sizing it may be assumed to be negligible in terms of overall system mass and cost.

Robotic subsystem: responsible for the construction of the SPS in LEO, and so is not affected to a large degree by the simplified system.

Structure subsystem: a simple structure was chosen in the Input worksheet, and thus mass or cost reductions cannot be realized directly. However, it is assumed that both solar arrays can be fixed to the one structure, so mass and cost savings are indirectly realized.

Telecommunications subsystem: ignored; negligible mass and cost as fraction of total SPS.

PMAD subsystem: The mass and cost of the cabling are eliminated, since very little cabling is required. Also, since the transmitter is fixed to the solar array, there is no need for a rotary joint.

However, a sizeable portion of the PMAD subsystem is attributed to the voltage converters, which are necessary to transfer GW order levels of power to the transmitter.

Thermal subsystem: incorporated throughout the SPS, and is evaluated in conjunction with the other subsystems.

Propulsion subsystem: required to move the SPS from LEO to GEO, is dependent solely upon the overall SPS mass, and so is automatically calculated.

Integration and testing: automatically evaluated according to the other subsystems.

Listed below is a summary of relevant output values, followed by the revised values generated by modifying the relevant values in the appropriate sub-system worksheets.

In table 4, it is assumed that a bifacial solar array can be produced at no additional cost or weight. Compared to the baseline, total mass savings is 3%, but total cost reduction is nearly 10%.

Table 4: Space Segment Model Output (1 GW ground power)
(cost and mass difference between baseline and fixed concept GEO SPS)

Subsystem	Mass (10 ³ kg)	Cost (\$M)	Mass (10 ³ kg)	Cost (\$M)	Change (%)	
					mass	cost
	Baseline		Fixed bifacial			
Power Trans.	1743	945	1743	945	0	0
Solar Conversion	4526	4532	4526	4532	0	0
A/C, Robotics	358	3636	200	2000	-44.1	-45.0
Struct., Telecom.	3959	1933	3649	1782	-7.8	-7.8
PMAD	2204	498	2164	434	-1.8	-12.8
Propulsion	783		783			0
Thermal	2766	5722	2766	5722	0	0
Integration & Test		4049		3784		-6.5
Totals	16339	21315	15 831	19199	-3.1	-9.9

The summary is that the revised design reduces the amount of energy produced by a factor of $2/\pi$ (64% of the baseline power), at a cost reduction of 9.9%. The produced power is thus 141% as expensive, per kW-hour, than power from the baseline concept.

The evaluation changes dramatically if the bifacial array is accounted as twice the mass and twice the cost of a single-sided array. A bi-facial array will then add an additional 4526 tonnes to the satellite mass, and increase satellite cost by \$4532 M. These represent increases of 25% and 11% in mass and cost, respectively, compared to the baseline system. In this case, power from the revised design is 174% as expensive (per gigawatt-hour) as the power from the baseline design. In this analysis, the cost associated with an additional solar array is substantially greater than the mass and cost savings realized through satellite design simplification.

It was anticipated that cost reductions from a simplified power management and distribution (PMAD) system would be large, however, the PMAD system accounts for only 2% of the overall system cost, regardless of it being a substantial portion of the system mass. Therefore PMAD cost savings do not have a large effect on the overall system cost, and consequently is unable to offset the increased costs from the additional solar array.

For the proposed concept to be lower in cost than the baseline, it is necessary that the cost per watt of the solar cells be reduced significantly. For example, a 50% reduction in thin film photovoltaic cell cost, from \$1/watt to \$0.50/watt [9], would result in a system cost equal to that of a single-array SPS. In other words, the previously calculated savings of 3% mass reduction and 10% cost reduction would be

possible. The proposed SPS design could then become economically feasible (at least according to a first-order calculation).

Examination of the power price profiles for candidate urban areas, indicated that the cosine power production peaking at sunrise and sunset did not well match near-term power demand. Even if a noon-peaked solar generation is subtracted from the demand curve, the power profile still does not perfectly match requirements [14]. Much of the power is produced when the power demand is very low (e.g., before 8 AM), and electricity price is low.

Since the power profile of the proposed design is not suited for selling at peak demand, and much of the power produced will not be sold at peak price, the higher energy cost per gigawatt-hour means that the design is not economically feasible in the near-term compared to the baseline (although if in the future ground solar makes massive contributions to future terrestrial power, this conclusion should be revisited).

7 Fixed Design with integrated microwave transmitter: the "8 AM/4 PM" design.

If the design constraint of a single array is relaxed, two arrays can be baselined, and the arrays can be tilted outward to accommodate the actual demand peak (after subtraction of solar) at 8 AM and 4 PM (or other times chosen to fit the peak demand). With the addition of tilt, it is no longer true that the microwave beam is perpendicular to the solar arrays. The backside of each solar array is in the view of the Earth.

A significant difficulty of the earlier design is the fact that the initial size of the system requires an extremely high initial investment. Due to the risk of the investment (market risk as well as technical), such investment is unlikely to occur.

The redesign of the solar power satellite opens the possibility of integrating the solar array directly to the microwave transmission [5,6]. By placing solid-state microwave transmitters directly on the back of the solar array, power management and distribution, as well as all voltage conversion, is eliminated.

Figure 9 shows the conceptual design for a satellite to deliver maximum power at 8 AM and 4 PM, where the back side of each array is an integrated microwave transmitter. This design was presented at the third SERT technical integration meeting [13].

The advantages of integration of the solar arrays and the transmitter are discussed in reference [5] and [6]. By integrating solar array with the microwave transmitter, the transmitter aperture becomes as large as the solar array area. This results in a narrower beam. A narrow beam allows smaller rectenna areas, thereby permitting much smaller solar power satellites. The smaller scale reduces the initial capital investment.

For "conventional" SPS designs, the ratio of solar array area to the transmitter array area is approximately a factor of 64. For example:

- 1979 "Reference" system: 50 km² solar array, 0.8 km² transmitter (area ratio 64)
- 1999 "Abacus" system: 12 km² solar array, 0.2 km² transmitter (area ratio 64)

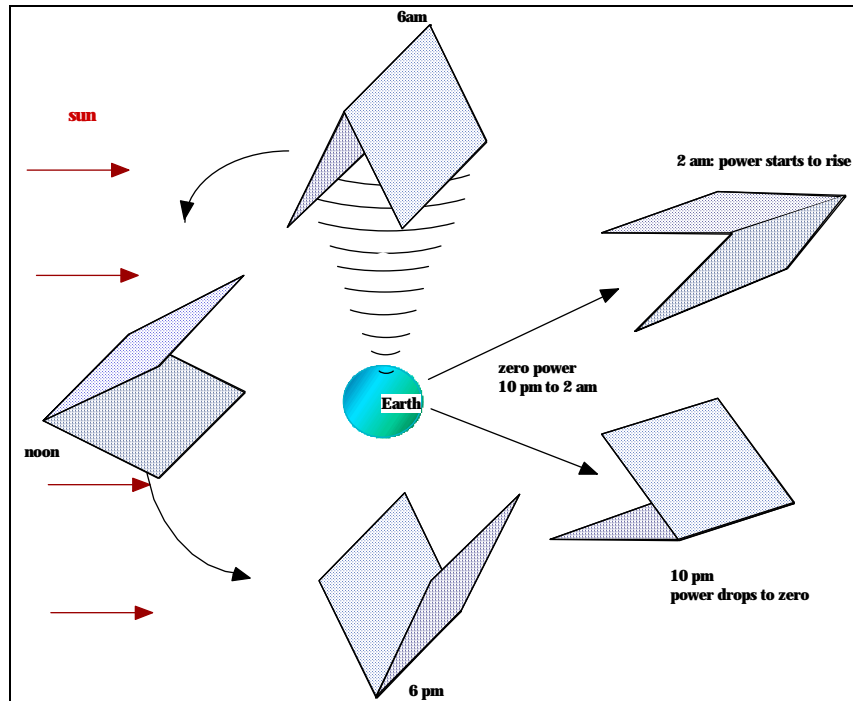


Figure 9: notional design for a solar power satellite to deliver peak power at 9 AM and 4 PM.

Design features:

- Very large scale integration
- Each solar-array element incorporates microwave transistor on reverse side
- Reverse side of solar array acts as phased array antenna (Phase signal must be distributed to each element)

For the integrated design, the transmitter area equals the solar array area. For the same power density on the ground, the minimum system size decreases in power by a factor of 4 for the 4 PM/8 AM tilt design. The rectenna area scales proportionately, and the minimum investment cost to first power decreases.

Overall, an integrated 4 PM/8 AM fixed delivers same peak power, but $2/\pi$ (64%) lower total energy than a fully tracking SPS. The power is delivered at peak-power rates, not baseline power rates, resulting in two times higher revenue per kW-hr. Thus, the integrated SPS delivers 27% more revenue at 30% lower cost. **The bottom line is that the integrated SPS delivers power at 45% lower cost.**

By reducing the size of the SPS to take advantage of the narrower beam, an integrated SPS can be decreased in power by factor of 4. This means that the cost to first power can be reduced by factor of 5.7. Since the investment required to reach first return is the major showstopper for the economic case for space solar power, this is a significant improvement in the design.

8 Fixed Design with integrated microwave transmitter: the "Slab" One-sided array

The 8 AM/4 PM design has two leaves in a "dihedral" configuration. It is evident, however, that the operation of the two leaves are independent of each other. This brings up the possibility of making a solar power satellite with just a single leaf: a "slab" design, with the solar energy incident on one side and the power beamed out the other.

For the same power density on the ground, the minimum system size decreases in power by a factor of 8 for a face-on solar array. This is even better than the factor of 4 found for the 4 PM/8 AM tilt.

The tilt of the system can be chosen to provide power that is optimally adjusted to the peak power requirements. For example, a tilt of 30 degrees could be used to provide peak power at 2 PM. This matches the maximum power demand of urban areas in the United States. This peak can be adjusted forward or back, subject to the constraint that peaks at (or near) 6 AM and 6 PM are not possible, since these would require the array to be edge-on to the direction of microwave beam. Figure 10 shows a "slab" one-sided array tilted to produce peak power at 2 PM.

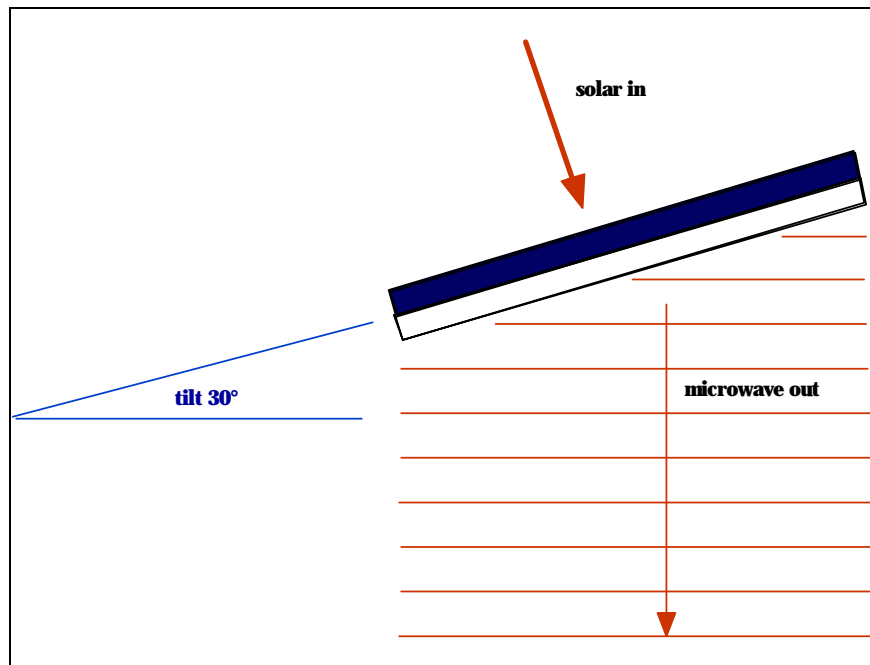


Figure 10. "Slab" single-sheet solar array, tilted to provide peak power at 2 PM.

In this design, the 2 PM tilt is not a gravity-gradient equilibrium. Maintaining the tilt will require stabilization. For example, a gravity-gradient boom could be deployed downward on a truss to put the system into gravity-gradient stability.

An alternate version would be to orient the solar array horizontally, and to direct the beam at an angle, to reach a receiver located at a slightly eastward latitude. The horizontal orientation is an equilibrium in the gravitational field, but weakly unstable (this is the orientation of the ISS, for example). By aiming the power beam approximately 2500 km east, the "noon" power beam generation for the satellite can be received at 2 PM.

Table 5: "Slab" Solar Power Concept:

- solar integrated to microwave
- no moving parts
- fixed orientation
- peak power at 2 PM (matches demand peak)
- zero power 8 PM to 8 AM

Table 6 shows a space-segment model of the "slab" design. The cost of the design is 64% of the cost of the conventional tracking array. The conclusions of this analysis are:

- Lower total energy, but power is matched to peak demand
- At the same size, system delivers 64% of the power at 64% of the cost
- But power sells at 2 PM peak power rates, not baseline power rates
- minimum size can smaller by factor of 8
- Eight times lower investment to first power
- 8 times more attractive

9 Comparison of output from SPS to data on urban electrical demand profiles

To examine the economics of the solar power satellite, the fixed geosynchronous designs were compared to the price and power demand profiles of several large urban electrical markets (primarily Boston and New York area), both with and without the assumption of a terrestrial solar energy generation to provide power during the daytime [14].

Details of the spreadsheets with these results were presented at the 3rd Technical Interchange Meeting [13] of the SERT project. These results, in general, tended to verify the analysis presented above. It is interesting to note, however, that the actual market pricing of electricity can have significant spikes of over ten times the average price per kilowatt hour (and in some cases significantly more). If a system could be developed to selectively meet these high-price demand spikes, an extremely high premium could be charged, albeit for only a short time.

Subsystem	Mass 10 ³ kg	Cost (\$M)	Mass 10 ³ kg	Cost (\$M)	% cost Change
	Baseline		Integrated		
Power Trans.	1743	945	0	0	-100
Solar Conv.	4526	4532	4526	4532	0
A/C, Robotics	358	3636	200	2000	-45.0
Struct. & com.	3959	1933	3959	1933	0
PMAD	2204	498	0	0	-100
Propulsion	783	-	648	-	0
Thermal	2766	5722	0	0	-100
Integ. & Test	-	4049	-	2025	-50
Totals	16 339	21315	9333	10490	-36

Conclusions

A space solar power generation system can be designed to work in synergy with ground solar power. Previous Space Solar Power architectures were designed to deliver 24-hour power; this design constraint was relaxed. A non-tracking, integrated solar/microwave Space Power system can be configured to match peak power demand. The minimum system size decreases in power by:

- factor of 8 (face-on solar array)
- factor of 4 (4 PM/8 AM tilt)

The ground rectenna scales proportionately. Since the minimum investment required to reach first power decreases, this design is considerably more feasible than tracking system concepts.

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14. G. Landis, "Peak Power Markets for Satellite Solar Power," paper IAC-02-R.3.06, 53rd International Astronautical Congress/2002 World Space Congress, Houston TX, 10-19 October 2002.

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