

# A Comparison of a Solar Power Satellite Concept to a Concentrating Solar Power System

David V. Smitherman\*

NASA Marshall Space Flight Center, Huntsville, AL, 35812

A comparison is made of a solar power satellite (SPS) concept in geostationary Earth orbit to a concentrating solar power (CSP) system on the ground to analyze overall efficiencies of each infrastructure from solar radiance at 1 AU to conversion and transmission of electrical energy into the power grid on the Earth's surface. Each system is sized for a 1-gigawatt output to the power grid and then further analyzed to determine primary collector infrastructure areas. Findings indicate that even though the SPS concept has a higher end-to-end efficiency, the combined space and ground collector infrastructure is still about the same size as a comparable CSP system on the ground.

## Nomenclature

<i>AU</i>	=	astronomical unit
<i>B</i>	=	billion
<i>CSP</i>	=	concentrating solar power
<i>DC</i>	=	direct current
<i>DOE</i>	=	Department Of Energy
<i>GEO</i>	=	geostationary Earth orbit
<i>GW</i>	=	gigawatt
<i>GWh</i>	=	gigawatt hour
<i>km</i>	=	kilometers
<i>m</i>	=	meters
<i>MW</i>	=	megawatt
<i>MSFC</i>	=	Marshall Space Flight Center
<i>NASA</i>	=	National Aeronautics and Space Administration
<i>NREL</i>	=	National Renewable Energy Laboratory
<i>PV</i>	=	photovoltaic
<i>RF</i>	=	radio frequency
<i>SoDa</i>	=	solar radiation data
<i>SPS</i>	=	solar power satellite
<i>TRL</i>	=	Technology Readiness Level
<i>W/m<sup>2</sup></i>	=	watts per square meter

## I. Introduction

SOLAR power satellite (SPS) concepts have been proposed and promoted since the 1970s as a possible solution for providing clean energy for use on Earth. When comparisons are made with ground-based solar power systems, the space-based system is often favored due to the poor performance of the ground-based photovoltaic (PV) arrays, interference by weather, and day/night cycles. Further research indicates that there is little information available on the viability of an SPS concept in comparison with a ground-based concentrating solar power (CSP) system. This paper makes a first-order comparison of a 1-gigawatt (GW) SPS concept located in geostationary Earth orbit (GEO) to a 1-GW ground-based CSP system that has been scaled up from an operational CSP facility.

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\*Technical Manager, Advanced Concepts Office, ED04, AIAA Senior Member

## II. Solar Power Satellite Concept

Peter Glaser and Arthur D. Little, Inc. first investigated the SPS concept for the National Aeronautics and Space Administration (NASA) in their 1974 report, *Feasibility Study of a Satellite Solar Power Station*.<sup>1</sup> More detailed analysis followed by both NASA and the Department of Energy (DOE) in a number of reports including the 1980 *Satellite Power System Concept Development and Evaluation Program Assessment Report*.<sup>2</sup> Findings indicated that there were many uncertainties as to the feasibility of SPS systems and that additional research and technology development was needed, including the development of lower cost space infrastructures to make solar power from space feasible.

A reference concept from the NASA/DOE studies for an SPS is illustrated in Fig. 1. It is a 5-GW system with a large 50-km<sup>2</sup> solar cell array in GEO that converts sunlight to electrical energy, which is then transmitted to Earth by microwaves from a 1-km diameter antenna. The microwaves are collected on the ground by a rectifying antenna measuring 10 km in diameter and then converted to electrical energy that can be fed directly into the power grid on Earth. At 35 degrees latitude Fig. 1 indicates that the ground spot for the rectifying antenna warps into a 10 km by 13 km ellipse.

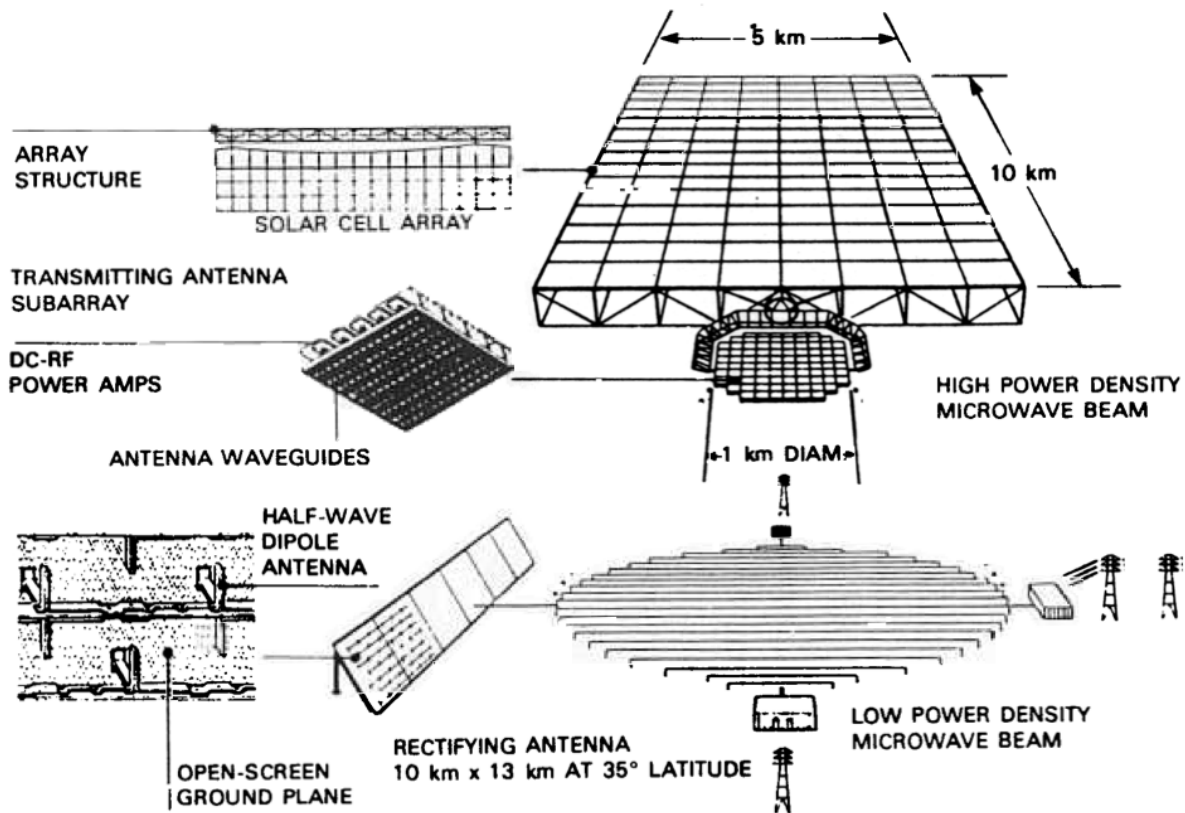


Figure 1. Solar power satellite reference concept.<sup>2</sup>

Many variations of this concept can be found in the published literature as illustrated by the 1.2-GW systems described in Fig. 2 for the Abacus Satellite and the Integrated Symmetrical Concentrator Satellite described in Fig. 3. The Abacus Satellite has a similar configuration to the reference design shown in Fig. 1, but is smaller to approach a more manageable mass and scale for assembly and operations. The Integrated Symmetrical Concentrator Satellite is more complex in appearance because it uses reflectors to concentrate sunlight onto a smaller PV array. Using these systems and the reference concept as a starting point, a general analysis was made to explore the overall efficiency and size of a 1-GW SPS concept in space compared to a 1-GW CSP system on the ground.

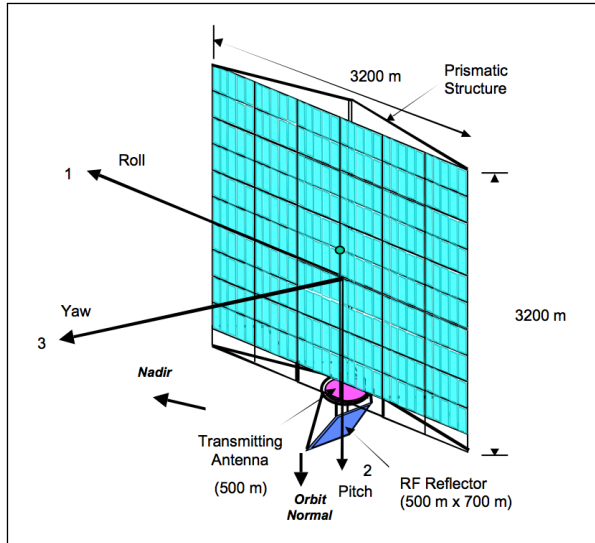


Figure 2. Abacus Satellite concept.<sup>3</sup>

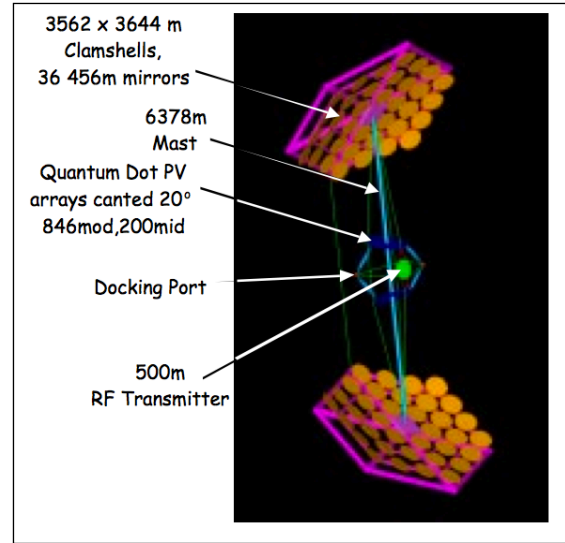


Figure 3. Integrated Symmetrical Concentrator Satellite concept.<sup>3</sup>

Table 1 provides general efficiency information for the referenced SPS configurations using microwave transmission. Note that the single largest drop in efficiency is with the PV array, and that the remaining losses are due to the many steps in the conversion process from sunlight to grid power. Improvements in PV efficiency will reduce the size of the collectors for the space segment, but will have little impact on the remaining systems. Some SPS designs use reflectors as an additional step in the transmission process. For example, the Abacus Satellite in Fig. 2 uses a radio frequency (RF) reflector for microwave beam steering, and the Integrated Symmetrical Concentrator Satellite in Fig. 3 uses large reflectors as the main solar collectors to focus sunlight onto a smaller PV array. The SPS reference design in Fig. 1 does not use reflectors and so a separate line item for reflectors is not included in the efficiency calculations in Table 1.

Table 1. Solar power satellite efficiency.

Segment	Efficiency	Power (W/m <sup>2</sup> )	Notes
Sunlight	100%	1367	Maximum on a flat panel in space
Photovoltaic conversion to DC	30%	410	Best predicted solar cell efficiency
Power management and distribution	99%	406	
DC to RF conversion	85%	345	
Microwave antenna phase scan losses	90%	311	
Atmospheric attenuation to microwave transmission	90%	280	Desert dry air conditions
RF collection area efficiency	90%	252	
RF to DC conversion by rectenna	90%	226	
DC to AC conversion	94%	213	Supplies electricity to grid frequency
Power management and distribution	95%	202	
Total end-to-end efficiency	14.79%	202	Best predicted

Based on the efficiency data provided in Table 1, it is possible to derive an approximate size of the major elements for an SPS concept. Table 2 uses the end-to-end efficiency from Table 1 to derive a collection area for a 1-GW system. In the Abacus Satellite concept, the collector area is the PV array; in the Integrated Symmetrical Concentrator Satellite, the collector areas are the two large concentrating reflectors. Both systems have microwave transmitters that are about the same size. As previously noted, the reference system does not utilize reflectors, so the areas associated with the additional systems for the Abacus Satellite and Integrated Symmetrical Concentrator Satellite were not included. If they were included the total system area in space would increase 0.35 km<sup>2</sup> for the RF reflector on the Abacus Satellite, and perhaps an additional 0.40 km<sup>2</sup> for the PV array on the Integrated Symmetrical Concentrator Satellite.

An average power density of 100 W/m<sup>2</sup> governs the rectifying antenna area. The actual power density will vary depending on the design of the system, but in general it will peak at around 200 W/m<sup>2</sup> to 300 W/m<sup>2</sup> in the center of the rectenna and taper off at the edges to a few W/m<sup>2</sup>. A large keep-out zone is included around the perimeter where exposure to low-level microwaves might be possible. The actual rectenna size may vary according to location as indicated by the reference design in Fig. 1 where the rectenna is elliptical due to the beam angle at the designated latitude.

**Table 2. Solar power satellite system area summary sized for 1 GW output.**

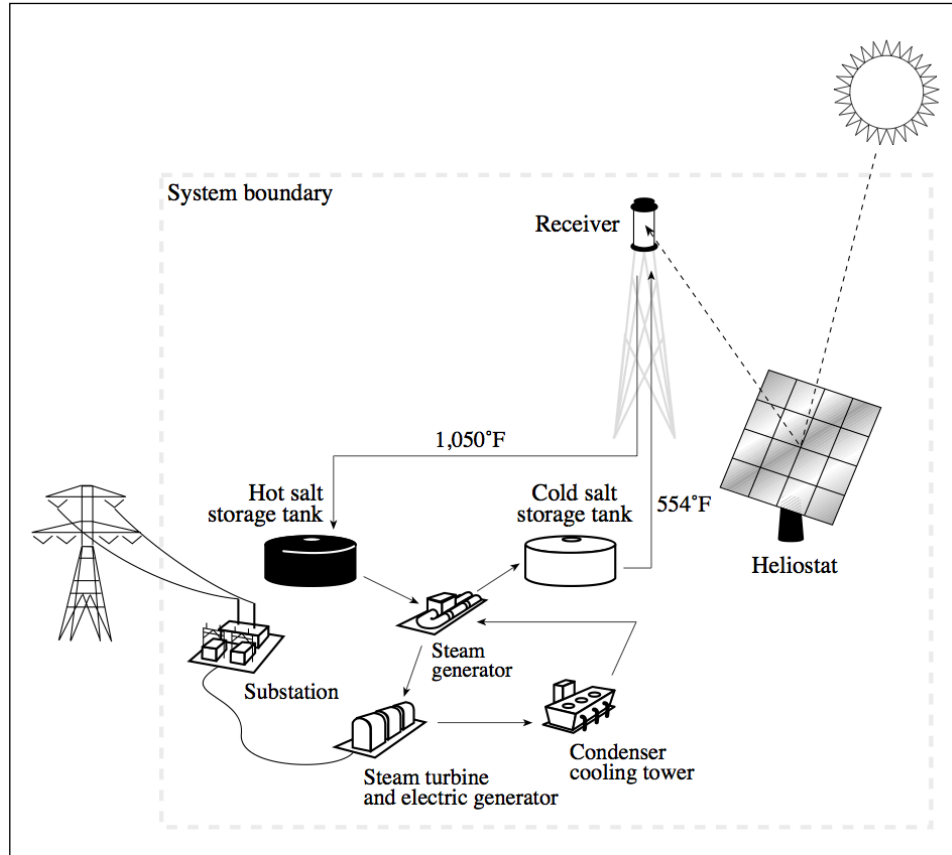
Segment	System Area (km <sup>2</sup> )	Notes
Solar Collector Area	4.95	Sized for 1 GW based on anticipated end-to-end efficiency
Microwave Transmitter Area	0.20	Based on Abacus and Integrated Symmetrical Concentrator concepts
Rectenna Receiver Area	10.00	Calculated from area required for 1 GW at an average energy density of 100 W/m <sup>2</sup> across the entire rectenna
Total System Area	15.15	Ground and space-systems area combined
Total Land Area	34.00	Includes keep-out zone calculated at 3.4 times the rectenna area

As previously noted there is a significant drop in end-to-end efficiency due to the PV solar cells listed at 30%. Additional analysis was done to determine how higher PV efficiencies could improve the overall system. It was found that increasing the solar cell efficiency to 50% would yield an end-to-end efficiency of 24.65% with an output of 337 W/m<sup>2</sup>, while increasing the solar cell efficiency to 90% would yield an overall efficiency of 44.37% with an output of 607 W/m<sup>2</sup>. Some solar cell technologies are approaching 50% efficiency,<sup>4</sup> which if possible would yield an SPS collector area of ~2.97 km<sup>2</sup>. Although 90% efficiency is highly unlikely it is useful to note that such a collector would still have an area of ~1.65 km<sup>2</sup> for a 1-GW system. The point of this exercise is to simply note that the size of the space segment is still quite large regardless of solar cell design, and that these efficiency improvements have no impact on the size of the ground infrastructure segment. In addition, any improvement in PV efficiency for SPS concepts will also improve the competitiveness of ground-based PV systems.

### III. Concentrating Solar Power System

CSP systems are in use today for power production. There are several design variations, but for the purposes of this comparison a CSP tower design was examined. Figure 4 describes the concept as an array of heliostats that focus sunlight onto a receiver at the top of a central tower. The heat energy collected by the receiver is transferred into a salt solution for storage in a large hot salt storage tank. The salt solution is then run through a heat exchanger to produce steam and drive electrical generators, which produce power to feed into a substation and the local power grid. The salt solution is cooled in the process and reused by circulating it through a cold salt storage tank and then back to the receiver. This process has many similarities to conventional nuclear, oil, gas, and coal fired steam power plants. A recent study by the DOE provides the following information for context as to the maturity of this technology.

Historically, CSP market growth has been sporadic. After a number of CSP plants were built in California in the late 1980s, almost 15 years passed before the next commercial CSP plant was built, followed by a number of new plants in the United States and Spain during 2007–2010. By the end of 2010, global CSP capacity was about 1,300 MW, with 512 MW in the United States and most of the rest in Spain. In the United States, almost 10 GW of CSP projects were under various stages of development at the end of 2010. Even if only a small fraction of these projects are built, the industry will experience very rapid growth in the near future.<sup>5</sup>



**Figure 4. Concentrating solar power system.**<sup>6</sup>

Table 3 provides general efficiency information that correlates with operational CSP systems in Spain and the southwestern United States. For example, the large drop in efficiency from the atmosphere, weather, and day/night cycle yields an output of about 243 W/m<sup>2</sup>, which corresponds with average solar radiation data of approximately 245 W/m<sup>2</sup> for a flat panel on the ground in Phoenix, Arizona. The next large drop in efficiency is in the power tower configuration rated at 14% based on molten salt tower designs.<sup>5</sup> The SPS concept has potential efficiency improvements as previously noted, and so does the CSP system. In general, the efficiency of steam turbine systems is much higher—around 44%.<sup>7</sup> Such improvements to the CSP tower system would yield an increase in the end-to-end efficiency from 4.83% to 15.18% with an output improvement from 66 W/m<sup>2</sup> to 208 W/m<sup>2</sup>, more than three times the current capability.

**Table 3. Concentrating Solar Power efficiency.**

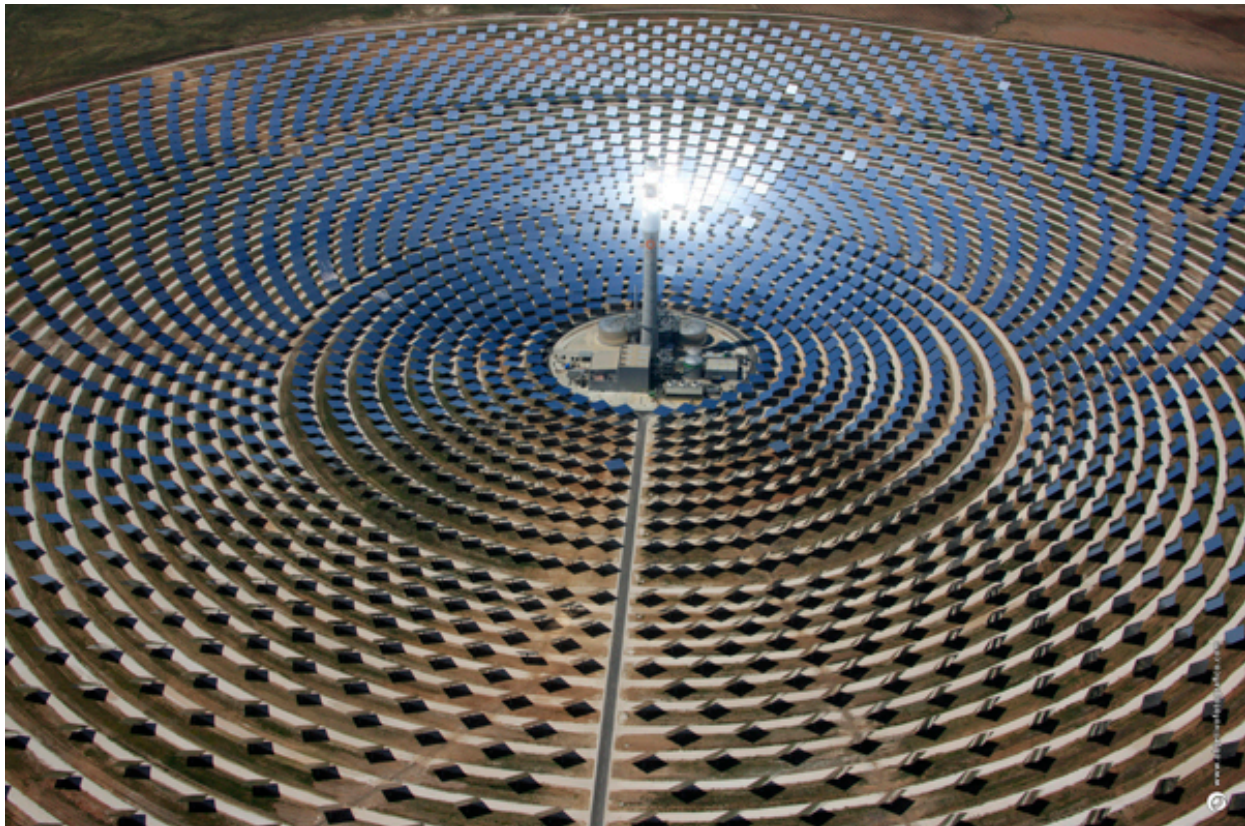
Segment	Efficiency	Power (W/m <sup>2</sup> )	Notes
Sunlight	100%	1367	Maximum on a flat panel in space
Atmospheric attenuation to sunlight	69%	943	Maximum for desert regions
Annual weather, H <sub>2</sub> O, hourly, & dust corrected irradiance	60%	566	Average daily direct on a flat panel in Phoenix, AZ
Day/night cycle	43%	243	Phoenix latitude is ~ 245 W/m <sup>2</sup> average
2-axis tracing	136%	331	Better than a flat panel; keeping incidence angle normal
Power Tower configuration	14%	46	14% is current efficiency rating
Night generation from thermal energy storage	150%	70	Heat storage in salt medium generates power at night
Power management and distribution	95%	66	
Total end-to-end efficiency	4.83%	66	Agrees with NREL efficiency predictions

Table 4 provides a summary of the area requirements for a 1-GW CSP system. It is unlikely that one tower would be sufficient. Instead, the installation would be a group of smaller 20 MW to 100 MW systems combined to achieve 1 GW in total output. The sizing in Table 4 is based on the Gemasolar Thermosolar Plant design in Fuentes de Andalucía, Spain, with a 19.9 MW capacity.<sup>8</sup> The panel collector area indicated is 15.15 km<sup>2</sup> for a 1-GW system. With the efficiency improvements noted, moving from 14% to 44%, there is a potential for CSP installations to reduce the collector area requirements from 15.15 km<sup>2</sup> to approximately 4.82 km<sup>2</sup> for a 1-GW system. Figure 5 is an aerial photograph of the referenced Gemasolar Thermosolar Plant. The developer describes the facility as follows.

Gemasolar is the first commercial plant in the world to use the high temperature tower receiver technology together with molten salt thermal storage of very long duration... Gemasolar was the first project of Torresol Energy to enter into operation in May 2011 and has an installed capacity of 19.9 MW of power being capable of supplying 110 GWh per year. Thus, it generates enough power to supply 27,500 households. Also, being a clean energy, it reduces by more than 30,000 tons per year the CO<sub>2</sub> emissions.<sup>9</sup>

**Table 4. Concentrating Solar Power systems area summary sized for 1 GW output.**

Segment	System Area (km <sup>2</sup> )	Notes
Solar Collector Area	15.15	Reflectors with power towers (probably ten 100-MW systems)
Total System Area	15.15	Calculated from area required for 1-GW output
Total Land Area	90.87	Area required to minimize shadowing of 2-axis tracking reflectors calculated at 6 times collector area



**Figure 5. Gemasolar Plant, owned by Torresol Energy, Torresol Energy Investments, S.A. in Fuentes de Andalucía, Spain.<sup>9</sup>**

#### IV. Comparing a Solar Power Satellite Concept to a Concentrating Solar Power System

Examining the end-to-end efficiency of each system and the projected scale of the two infrastructures makes a good comparison of the SPS concept to a CSP system. Table 5 provides this comparative analysis along with potential improvements that might be possible for each system. Following Table 5 is a comparative discussion of SPS and CSP attributes.

**Table 5. Solar Power Satellite to Concentrating Solar Power comparison for a 1-GW system.**

Segment	Solar Power Satellite Concept	Concentrating Solar Power System	Notes
<b>A. Technology Readiness Level (TRL)</b>	5	9	SPS individual technologies vary from TRL 2 to TRL 9. CSP is operational and rated at a TRL 9 for comparison.
<b>B. Space-Based Systems Area (Collector plus Transmitter)</b>	5.15 km <sup>2</sup> 3.17 km <sup>2</sup> potential	0.00 km <sup>2</sup>	SPS PV array efficiency improvements from 30% to 50% could reduce the space segment for SPS to 3.17 km <sup>2</sup> .
<b>C. Ground Receiver Type</b>	Rectenna	Heliostats with Power Towers	A concern with SPS Rectenna installations is the internal body heating caused by microwaves.
<b>D. Receiver Collection Area</b>	10.00 km <sup>2</sup>	15.15 km <sup>2</sup> 4.82 km <sup>2</sup> potential	SPS Rectenna area is fixed in size due to energy density concerns. CSP collector area could be reduced with power tower efficiency improvements.
<b>E. Total System Area</b>	15.15 km <sup>2</sup> 13.17 km <sup>2</sup> potential	15.15 km <sup>2</sup> 4.82 km <sup>2</sup> potential	A comparison of total system area for the SPS concept and the CSP system indicates that they are about the same, but with significant improvement potential for the CSP system.
<b>F. Receiver Land Area</b>	34.00 km <sup>2</sup>	90.87 km <sup>2</sup> 28.4 km <sup>2</sup> potential	The SPS receiver land area is fixed based on energy density. Total CSP land area is about 3 times larger, but has potential to match SPS linked to CSP efficiency improvements.
<b>G. Total End-to-End Efficiency</b>	14.79% 24.65% potential	4.83% 15.18% potential	End-to-end efficiency of SPS is much better than CSP.
<b>H. Power Output from Collector</b>	202 W/m <sup>2</sup> 337 W/m <sup>2</sup> potential	66 W/m <sup>2</sup> 208 W/m <sup>2</sup> potential	Power output per m <sup>2</sup> from the collector for SPS is more than twice that of CSP.

##### A. Technology Readiness Level

- 1) **SPS Concept:** The Technology Readiness Level (TRL) of individual SPS technologies varies from TRL 2 (technology concept and/or application formulated) to TRL 9 (actual system is flight proven through successful mission operations). For the purposes of this exercise the SPS concept was rated at an average of TRL 5 (component and/or breadboard validation in a relevant environment).
- 2) **CSP System:** For comparative purposes, the operational CSP system is rated at TRL 9 even though it is not a space system.

## B. Space-Based Systems Area

- 1) **SPS Concept:** PV array efficiency improvements from 30% to 50% could reduce the space segment for SPS from 5.15 km<sup>2</sup> to 3.17 km<sup>2</sup>. Current solar cell developments indicate that this efficiency improvement is reasonable, but the size of the collector in space is still significant.
- 2) **CSP System:** The advantage of a CSP system is that it is a ground-based system with no space infrastructure segment.

## C. Ground Receiver Type

- 1) **SPS Concept:** A concern with SPS rectenna installations is the potential for internal body heating caused by exposure to microwaves at the rectenna site. Many studies cite the exposure to microwaves as a potential health concern for humans, wildlife, plant life, and as an unknown operational concern for aircraft and satellites. These uncertainties require further investigation.
- 2) **CSP System:** The operational safety of the ground collector segment for the CSP system is proven.

## D. Receiver Collection Area

- 1) **SPS Concept:** The rectenna area for the SPS concept is likely to be fixed in size due to the microwave energy density concerns. At northern latitudes the microwave beam angle could cause the rectenna size to grow into an ellipse as indicated in the Fig. 1 reference design.
- 2) **CSP System:** The reflector area for the CSP system has potential for reduction with CSP system efficiency improvements. Such improvements are likely as the market for CSP systems grows and becomes more competitive.

## E. Total System Area

A comparison of the total system area for the SPS concept and the CSP system indicates that they are about the same size.

- 1) **SPS Concept:** The SPS concept has potential for some system-area reductions in the space segment with improvements to PV technology.
- 2) **CSP System:** The CSP system has potential for significant reductions in system-area requirements linked directly to improvements to CSP system efficiency.

## F. Receiver Land Area

- 1) **SPS Concept:** The SPS concept total land area including the keep-out zone is likely fixed based on energy density restrictions and safety concerns.
- 2) **CSP System:** The CSP system land area is three times greater than SPS requirements, but has potential for significant reductions that are linked to potential improvements in CSP system efficiency.

## G. Total End-to-End Efficiency

- 1) **SPS Concept:** The end-to-end efficiency of the SPS concept is estimated to be much better than the CSP system.
- 2) **CSP System:** Even though the end-to-end efficiency of the CSP system is not as high as the SPS concept, it still has significant advantages since it has no space infrastructure segment.

## H. Power Output from Collector

- 1) **SPS Concept:** Power output from the collector for the SPS concept is estimated to be more than twice that of the CSP system.
- 2) **CSP System:** The CSP system is about the same size as the SPS combined space and ground segments, but requires no space infrastructure for delivery, construction, maintenance, or repair.

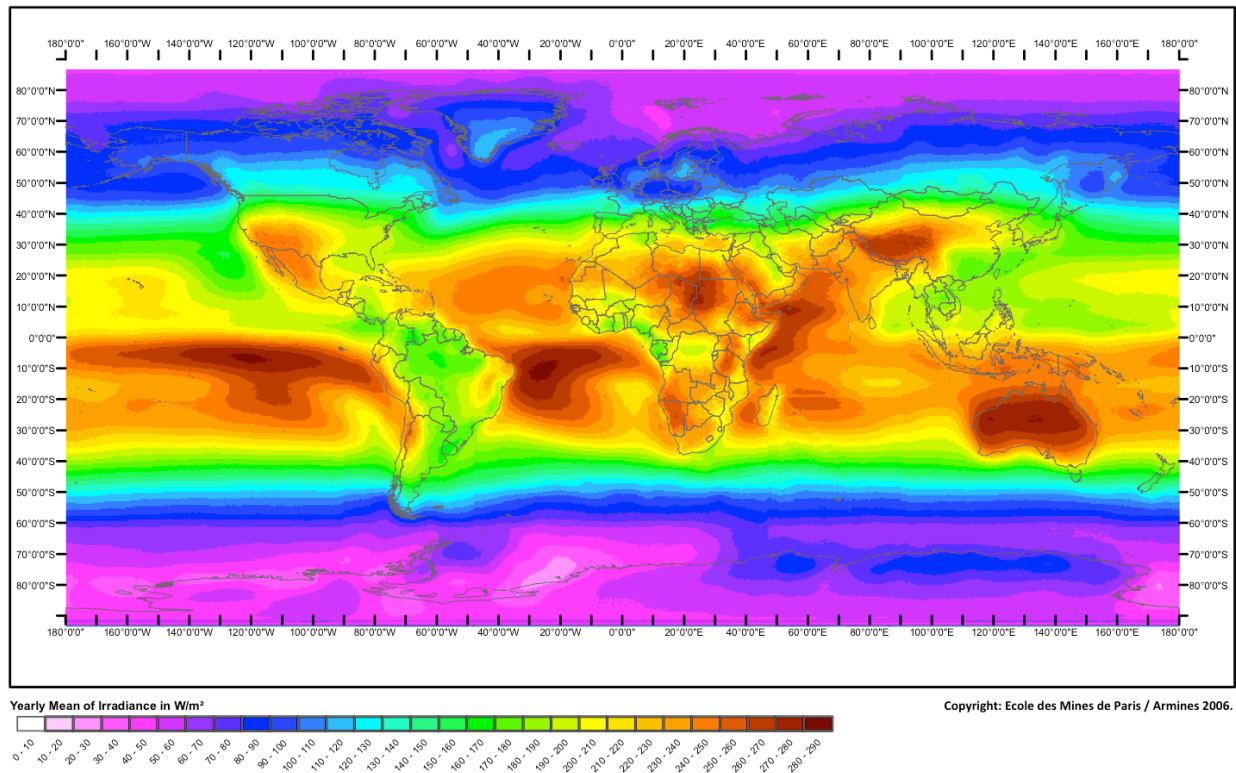
## V. Land Use

Land-use comparisons are needed because it is apparent that the ground segments for the SPS concept and the CSP system are both very large. For the SPS concept there is a health concern due to microwave exposure, and the rectenna area appears to be fixed in size based on the energy density of the microwave beam. The CSP system uses natural sunlight so the only concern is the large land-area required for generating power. A recent DOE study investigated the CSP system land-area requirements and noted the following:

After implementing the appropriate insolation, slope, and land-use filters, 22,593,000 hectare are available in the seven states considered to be most CSP compatible: Arizona, California, Colorado, Nevada, New Mexico, Texas, and Utah. This relatively small land area amounts to nearly 7,500 GW of resource potential and more than 17.5 million gigawatt-hours of annual generating capacity, assuming a capacity factor of 27%. The potential generating capacity exceeds the total U.S. electric grid capacity by a factor of more than six, while the potential energy production exceeds U.S. demand by a factor of more than four.<sup>5</sup>



It is also interesting to note that the land area available for CSP installations around the world is abundant. On average the solar radiation above the Earth's atmosphere is about  $1367 \text{ W/m}^2$ , and about  $1000 \text{ W/m}^2$  at the Earth's surface at mid-day. Variations occur due to weather patterns with the largest impact coming from the day/night cycle. The solar energy plants that were examined in this study are currently operating in areas that receive average solar radiation levels between  $195 \text{ W/m}^2$  and  $245 \text{ W/m}^2$  in Fuentes de Andalucía, Spain, and Florida and Arizona in the United States. Figure 6 provides a global solar radiation data map averaged from 1990 to 2004 where this range is depicted by the color code from yellow-green to orange. The darker red-orange areas are even higher, up to  $290 \text{ W/m}^2$  in parts of Africa, Asia, and Australia. Based on this global data there appears to be significant land areas with CSP potential on every continent except perhaps Antarctica.



**Figure 6. Averaged global solar radiation from 1990 to 2004.<sup>10</sup>**

Distribution of power from remote regions to population centers will need to be considered as the market grows for CSP installations. There are already long transmission lines in operation where a coal-fired steam power plant in Utah supplies power over a 788-km transmission line to southern California.<sup>11</sup> Transmission lines that are thousands of kilometers in length appear possible and will likely become economically practical as the CSP market grows.<sup>12</sup>

Another finding is that PV systems appear to be ideally suited for integration into population centers where no additional dedicated land area is required. PV installations on building rooftops and over parking areas are examples of how these systems can be integrated into an urban environment with no additional land use impact. As the cost for PV systems comes down, and their reliability and efficiencies improve, the practicality for broad use in the inner cities is likely.

## VI. Cost

A detailed cost analysis of an SPS concept against a CSP system was not prepared. However, a comparison was made to judge the physical scale of the SPS concept in comparison with a CSP system based on the relative physical size of each infrastructure. Table 5 indicates that an SPS concept requires approximately  $5.15 \text{ km}^2$  of constructed systems in space plus an additional  $10 \text{ km}^2$  of constructed systems on the ground for an output of 1 GW to the power grid. This yields a total of  $15.15 \text{ km}^2$  of constructed systems for the SPS concept. The CSP system examined also required about  $15.15 \text{ km}^2$  of constructed systems to produce 1 GW of power. Therefore, both systems using today's technology require about the same amount of total-constructed systems area to produce the same amount of power.

The major differences are in the cost of space systems and operations for the SPS concept and the cost of land for the CSP system. As noted in the previous section on land use, there is an abundance of land available for development of solar power systems around the globe. Table 5 indicates that the land-area requirements for the SPS concept is likely fixed at 34 km<sup>2</sup> for the ground rectenna and surrounding keep-out zone, whereas the CSP system area is likely to decrease from 15.15 km<sup>2</sup> to 4.82 km<sup>2</sup> and its land-area requirements from 90.87 km<sup>2</sup> to 28.4 km<sup>2</sup> as system efficiencies improve and the CSP industry matures. These efficiency improvements will likely make the total land-area requirements competitive with the total SPS rectenna land-area requirements in the near future.

Taking this analysis a step further, a rough order-of-magnitude cost estimate for the constructed systems area was prepared to confirm the physical scale observations. The SPS concept yielded a space array cost of \$4 B, not including launch cost, and a ground rectenna cost of \$2 B for a total materials cost of approximately \$6 B. Two ground-based systems were estimated: a PV system at \$8.9 B, derived from PV industry<sup>13</sup> reported cost; and a CSP system at \$2.1 B, derived from NREL published cost.<sup>8</sup> The SPS concept uses a PV array but is smaller than the ground-based PV system due to the higher solar flux available in orbit and the over-sizing of the ground system for night storage operations. Both systems are more costly than the CSP system due to their complexity and inefficiency. Adding launch cost to the SPS concept will add \$100 B to \$300 B at today's cost plus flights for orbital station keeping propellants, maintenance, and repair. These rough order-of-magnitude figures are interesting because they indicate that the CSP system is more cost effective than the SPS concept even without comparing the cost of space-systems delivery, construction, lifetime operations, maintenance, and repair.

## VII. Conclusions

Large SPS concepts in GEO for power transfer to Earth do not appear to be practical at this time when compared to current ground-based CSP systems. Even though the SPS concept has a higher end-to-end efficiency it does not appear capable of outperforming the CSP system when it comes to the size and complexity of the competing infrastructures. The SPS concept has both a large space infrastructure segment and a large ground infrastructure segment that is about equal to the total constructed systems area of a ground-based CSP system. The CSP system uses reflectors and a heat engine to produce power, and therefore avoids the inefficiencies of PV conversion of light to electricity. An additional benefit is that the CSP system can use heat as a storage medium making night operations possible, and significant improvements to the heat transfer and storage process appear likely as the industry matures. In general, it appears that ground-based CSP systems have great potential at many locations around the world.

Although reducing launch cost has been cited as a driver for the SPS feasibility in previous studies, this was not considered the only problem for the SPS concept and CSP system comparison. In addition to launch cost, there is the cost of on-orbit construction, maintenance and repair for SPS against the ground construction, maintenance, and repair of a ground-based CSP system. No detailed estimates were made; however, rough order-of-magnitude estimates indicate that the SPS concept launch cost was not the only problem that precludes it from being a practical system.

Through the development of this study, it was recognized that there are other applications for SPS concepts that should be investigated. These include further research into small low- to mid-earth orbiting SPS constellations that could supply airships and ground stations for remote area, military, and disaster relief applications; CSP technology development for space applications; and other high-efficiency, direct-energy conversion technologies that might improve overall efficiency of future SPS systems. Solar power satellite technologies will continue to be of interest to NASA including further development of PV arrays; microwave and laser transmission; and power storage and conversion technologies for space applications. These space applications of interest include all government and commercial satellite systems, robotic science and exploration missions, and future human missions beyond low-Earth-orbit to the Moon, asteroids, and Mars.

## Acknowledgments

This technical paper is based on the research and findings from a Space Solar Power study initiated by the NASA MSFC Advanced Concepts Office and Engineering Directorate in 2011 during the work-force transition period from the former Constellation Program to the current Space Launch System (SLS) Program. The intent was to explore the feasibility of Space Solar Power satellite applicability for power collection and transmission to Earth as a potential concept for development of a demonstration mission that could be launched on a future SLS vehicle.

Participants in the study were as follows:

David Smitherman	Larry Kos	Charles Meyers
Dan O'Neil	Scott Thomas	Teresa Miller
Janie Miernik	Peter Capizzo	Eric Ordonez
Leo Fabisinski	Susan Elrod	Dauphne Maples
Alayna Devineni	Karen Oliver	Scott Smith
Mike Baysinger	Karen Cunningham	Les Johnson

Final results from the study indicated that solar power in space was appropriate for space applications, but not currently practical for power transmission to Earth; therefore, no demonstration mission concept was developed. Subsequent development of this technical paper included additional technical material on operational CSP systems from the DOE and Torresol Energy as referenced.

### References

- <sup>1</sup>Glaser, P., Maynard, O. E., Mackoviak Jr., J., and Ralph, E. L., "Feasibility Study of a Satellite Solar Power Station," NASA CR-2357, February 1974.
- <sup>2</sup>DOE/NASA, "Satellite Power System Concept Development and Evaluation Program Assessment Report," U.S. Department of Energy, Office of Energy Research, DOE/ER/0085, November 1980.
- <sup>3</sup>Wie, B. and Roithmay, C. M., "Integrated Orbit, Attitude, and Structural Control Systems Design for Solar Power Satellites," NASA/TM-2001-210854, June 2001.
- <sup>4</sup>Green, M. A., Emery, K., Hishikawa, Y., and Warta, W., "Solar Cell Efficiency Tables (Version 36)," *Progress in Photovoltaics: Research and Applications* [online journal], Vol. 18, Issue 5, pp. 346-352, 18 June 2010, URL: <http://onlinelibrary.wiley.com/>, [cited 15 November 2012].
- <sup>5</sup>DOE, "SunShot Vision Study," DOE/GO-102012-3037, February 2012.
- <sup>6</sup>DOE, "Concentrating Solar Power: Energy from Mirrors," DOE/GO-102001-1147, FS 128, March 2001.
- <sup>7</sup>Spath, P. L., Mann, M. K., "Life Cycle Assessment of a Natural Gas Combined-Cycle Power Generation System," NREL/TP-570-27715, September 2000.
- <sup>8</sup>DOE National Renewable Energy Laboratory, "Concentrating Solar Power Projects, Gemasolar Thermosolar Plant," URL: [http://www.nrel.gov/csp/solarpaces/project\\_detail.cfm/projectID=40](http://www.nrel.gov/csp/solarpaces/project_detail.cfm/projectID=40) [cited 4 December 2012].
- <sup>9</sup>Torresol Energy, Gemasolar, URL: <http://www.torresolenergy.com/TORRESOL/gemasolar-plant/en>, [cited 7 December 2012].
- <sup>10</sup>SoDa, "Averaged Solar Radiation 1990-2004," copyright Mines ParisTech / Armines 2006, URL: [http://www.soda-is.com/eng/map/maps\\_for\\_free.html](http://www.soda-is.com/eng/map/maps_for_free.html), [cited 11 December 2012].
- <sup>11</sup>DOE, "National Transmission Grid Study," May 2002.
- <sup>12</sup>Paris, L., et al., "Present Limits of Very Long Distance Transmission Systems," Paper 37-12, International Conference on Large High Voltage Electric Systems, Paris, France, 1984.
- <sup>13</sup>Remmers, K. H., "PV Power Plants 2012, Industry Guide" Solarpraxis AG, Berlin, Germany, 2012.