Space-Based Solar Power:
Past and Future Implementation Strategies

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Solar Power Satellites – Abstract

The technology involved in solar power satellites (SPS) is simple: far above the earth, the satellite collects solar energy onto vast panel arrays, and transmits the energy to the Earth via microwaves, onto very large and efficient antennas. Such a simple technology already exists and promises untold amounts of renewable, clean, cheap, and reliable energy. Why, then, is space-based solar power not yet a reality? The answer is that solar-power satellites are very large constructs, and the tremendous cost to put such a large object into Earth orbit is currently far too expensive. In a 1978 DOE and NASA study, the minimum cost-to-orbit for a 5GW SPS (a three by six-mile construct) was estimated at about $3 trillion dollars. Such a structure was simply too large, the mass requirements were too great, and the cost-to-transport was too high. But in the 1997 NASA “Fresh Look” study, advances in SPS design yielded the innovative *concentrated photovoltaic* approach, which reduced mass and size without loss of power and efficiency. In addition, advances in aerospace engineering yielded a reduction in the cost-to-orbit: $10,000 per kilogram for low-earth orbit, and $40,000 per kilogram for Geostationary Earth Orbit (GEO). Unfortunately, the total cost-to-orbit for a SPS still remained at over $200 billion, with a gentle return on investment of over 20 years. It wasn’t until 2007, that the Department of Defense (DOD) created the National Strategic Space Office (NSSO) to investigate, on a continual basis, the feasibility of space-based solar power, including a solution to the seemingly intractable cost-to-orbit problem. Their study concluded that if the SPS adhered to a weight-to-power ratio of 3-6kg/watt and that the current cost-to-orbit was $3000/kg, then SBSP would be an attractive solution to the DOD’s expensive power requirements overseas. With a few changes in the implementation strategy of SBSP, the necessary weight-to-power and cost-to-orbit ratios are achievable and SBSP can be made profitable. However, it is important to acknowledge the long-term challenges associated with SBSP, such as space assembly, wireless transmission, public concerns, and international policy.
Space-Based Solar Power: Past and Future Implementation Strategies

1.0 Introduction

22,240 miles above the earth, in *geostationary earth orbit* (GEO), a vast structure over ten times the size of the International Space Station maintains its position over the equator. The satellite’s mirrored wings collect and focus a continuous torrent of sunlight onto giant platforms of solar arrays. Using solid-state electronics, the intense solar radiation is then converted into electric energy, which is then beamed electromagnetically to a fixed location on the earth, holding highly-efficient antennas the size of airports.

Does it sound like science-fiction? It isn’t. The complex physics for solar power satellites (SPS) was solved by 1978, and the underlying technology is available now. In addition, myriad studies have shown space-based solar power (SBSP) to be more powerful, environmentally friendly, reliable, and renewable than any other modern power source. Why, then, hasn’t SBSP become as commonplace as the power derived from fossil fuels? The simple answer is cost. Throughout history, investigations of SPS have repeatedly shown that the project deserves its reputation for being tremendously risky and outlandishly expensive, despite the vast benefits. The root of the problem lies in the staggering amount time and money that is required simply to transport the massive structure into orbit. As recently as a decade ago, all of this has remained true. However, recent advances in technology have resulted in an SPS with more power output, better design, and decreased size and mass. With smaller and lighter satellites, the initial cost-to-orbit also decreases dramatically. The question then becomes: “Are these advances sufficient to motivate government and commercial organizations to invest in SBSP? Is it now profitable?” To answer this, a fresh look at the modern energy landscape and the cost-to-first-power of SBSP is necessary.
2.0 Motivation

Profit alone is not the only force motivating the need for SBSP. Regardless of financial risk and return-of-investment, it is important to probe whether there is sufficient public and governmental need for the development of SBSP. Without the public awareness of the advantages of SBSP, and the understood inferiority of other sources of energy, SBSP will never become realizable. To put it simply, SBSP has the potential to single-handedly solve the energy crisis by combining the best aspects of fission and fossil fuels with the advantages of alternative energy.

<table>
<thead>
<tr>
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<th>Clean</th>
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<th>Base-load</th>
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<tr>
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<td>Yes</td>
<td>Decades remaining</td>
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<td>Yes</td>
<td>Fuel Limited</td>
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<td>Yes</td>
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<td>Yes</td>
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<td>Yes</td>
<td>Limited Qty – Competes w/Food</td>
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<td>Space Solar</td>
<td>Yes</td>
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</tbody>
</table>

(See Figure 2.)

2.1 Power Demand (Reliability, Resources, Power Generation)

Currently, the primary sources of global power generation are fossil fuels and nuclear fission. The high reliability, low cost, and large output of these two energy sources make them the only current solution to the base-load energy requirements of the Earth. Unfortunately, neither is a clean source of energy: nuclear power leaves nuclear waste, and the burning of fossil fuel causes air pollution. In addition, with international conflicts over diminishing resources, the proliferation of nuclear materials, and the skyrocketing cost of oil, these conventional power-generation methods are becoming increasingly unattractive and costly. SBSP, on the other hand, has the capacity to provide a nearly infinite amount of renewable energy without the environmental, economic, and political costs of conventional energy. (See Figure 2.)
2.2 Environmental Considerations

Typical alternative energy methods, such as solar and wind power, address the main disadvantages of conventional (fission and fossil fuels) power generation: alternative energy is continually renewable, and is minimally harmful to the environment. However, unlike fission and fossil fuels, alternative energy suffers from unreliability (such as shifting tides and the lack of sun), and the inability to meet base power demands. Accordingly, much energy efficiency and financial cost is expended to compensate for moments when alternative energy is simply not generating any power.

On the other hand, where terrestrial solar power is intermittent and is reduced by atmosphere by 75-80%, SBSP converts 99% of the sun’s power into energy at all times. (See Figure 3.) In addition, terrestrial solar power adversely effects the local environment far more than SBSP. Large habitats are destroyed by the vast surface area required for terrestrial solar power, and inefficient power conversion from photovoltaic cells result in vast build-ups of ambient heat. An SPS *rectenna*, on the other hand, generates no ambient heat and only blocks 10% of incoming light. Accordingly, the life and environment under the SBSP rectenna remains preserved, safe, and intact. (See Figure 4.)
3.0 Past Implementations

The concept behind solar-power satellites has been around for decades. It started in 1964, when William C. Brown provided the framework for SPS power transfer by successfully demonstrating a highly efficient, radio-controlled helicopter powered solely by microwaves. Then, four years later and not yet familiar with Brown’s research, Peter Glaser first proposed that solar collectors be placed in GEO and the power somehow transmitted to the earth. This idea was rejected by NASA because a method for transferring power wirelessly over extremely long-distances had not yet been developed. Although microwave power transmission was the ideal choice for SPS due to its extremely high power efficiency (at least 80%), the technology that Brown had demonstrated was then limited to short distances. After years of research, Glaser extended Brown’s microwave technology and was granted a patent in 1973 for transmitting microwave power over long distances. Thus the technology for SPS became available; solving the physics was all that remained.

3.1 The 1978 DOE & NASA Study [8]

Due to the 1970’s oil crisis, the DOE and NASA began seriously to investigate the feasibility of Glaser’s SPS. This effort then evolved into a much larger study, authorized by US Congress, which took place in the late 1970’s and early 1980’s. All aspects of SBSP were investigated, ranging from public acceptance to its international politics. In addition, the project was judged technically feasible: the technology was available, SPS designs were agreed upon, and the physics were completely solved. However, ignoring all other
expenses, simply transporting the SPS into orbit was estimated at a cost of $250 billion (this was later shown to be an underestimate of about $3 trillion). In addition, the time required to launch and assemble a 5GW (gigawatt) SPS -- a six-mile by three-mile construct -- was calculated to take a minimum of eight years and 280 launches. To place the desired 60 SPS in orbit, this meant that it would take at least 480 years to do so! Despite NASA’s conclusion that the project was technically feasible, a cursory analysis of the costs indicated that the project was economically unachievable. The cost-to-orbit was too high, and the launch frequency was too low. After the DOE’s critical analysis of the project, the project gained a reputation for being tremendous in size and outlandishly expensive, which is why support for SBSP soon waned.

3.2 The 1997 NASA “Fresh Look” Study [2]

Due to rising demand for energy and the mounting costs of fossil fuels, NASA felt that the technological advances made in the prior two decades merited a “fresh look” at SBSP. NASA noted that advances in technology and improvements to overall SPS design yielded a far simpler, smaller, and lightweight construct. One reason was that concentrated photovoltaic (CPV) designs became the new standard: achieving higher power and smaller mass through the use of featherweight mirrors concentrating sunlight onto fewer photovoltaic cells. In addition, thin-film photovoltaic cells became more affordable, lightweight, and efficient. Lighter mass and smaller size meant less cost-to-space transport; the factor most crippling to the
implementation of an SPS. Most importantly, in the prior two decades, the cost of space transportation had declined to a range of between $10,000/kg. for Low Earth Orbit (LEO) and $40,000/kg. for GEO. Although these advances created a remarkable reduction in the initial investment to implement SBSP, the cost of space transport forced the project to remain economically unachievable.

However, the 1997 study was not without hope. Citing exponential advances in technology, and an anticipated decrease in the cost-to-orbit, the study outlined a roadmap with an initial cost of $200 billion and a potential return of investment after about 15 years. The success hinged on the fact that frequent space travel would create cheaper space travel. For example, by making 52 launches a year, NASA outlined that the future cost per kilogram to Middle Earth Orbit (MEO) could drop from $20,000/kg to $400/kg. Unfortunately, this conclusion was criticized as being tremendously optimistic, and support for the project waned yet again. Without significant advances in technology and the decrease in cost to orbit, SPS remained economically unfeasible for the time being.

3.3 2007-2008 DOD and USAF Interest [5,6]

In 2007, the DOD and the U.S. Air Force began to independently study the feasibility of SBSP. With the cost of oil skyrocketing to a price of $120/barrel, the DOD has become concerned about the tremendous cost of providing power to overseas operations ($1/Kw). In addition, one of the mandates of the DOD is to prevent international conflicts that might escalate into war. As resources dwindle and prices rise, the U.S. may soon find herself in the midst of an unfavorable and highly-tense political situation. It is for these reasons that the
DOD created the National Security Space Office (NSSO) to investigate SBSP. Through the collaborative effort of over 170 scientific, academic, technical, legal, and business experts in the field of SBSP, the NSSO has released the first fully viable implementation of SBSP. They have concluded that SBSP has reached the point of practical and economic feasibility; that the project can be developed in a reasonable amount of time, and that it will create profit. However, the NSSO study stressed that the project remained tremendous in scope: a complicated engineering project with substantial challenges and a multi-disciplinary scope that is simply staggering. Their recommendation was that a strategic investment in certain challenge areas was necessary to help facilitate the swift implementation of SBSP.

4.0 Cost-to-Orbit Challenge

Among these challenges, the NSSO primarily stressed that two high-level goals regarding space transportation must be achieved. First, the total mass of the SPS cannot be greater than 3-6 kilograms for each watt of energy that it delivers to the ground. Second, the cost to deliver a kilogram of mass into orbit (MEO) cannot be greater than $3000/kg. Accordingly, this yields a highly efficient SPS with a total installed cost of $10,000 per kilowatt. This initial cost and rate of power delivery is competitive with the DOD’s current method of powering overseas operations.

4.1 Reducing Mass and Increasing Efficiency

As described in the 1997 “Fresh Look” study, to achieve high power and low mass in a SPS, a Concentrated Photovoltaic (CPV) SPS is a necessary start. However, additional measures need to be implemented to achieve the desired 3-6kg/W. Firstly, using higher efficiency solar cells creates an increase in power output, and dramatic decrease in mass. For example, DARPA’s “prism” solar cells at around 42.8% efficiency would reduce the size of a SPS by about 80%, while providing the same amount of power. In addition, all of the power cables, thermal management, altitude control that went along with managing a larger SPS, disappeared along
with the reduction of the solar array. These measures, combined with an efficient CPV SPS design, should more than satisfy the optimal 3-6kg/W specification.

4.2 Reducing Cost-To-Orbit

How can we achieve a cost to orbit of $3000/kg? In addition to reducing SPS mass, the answer lies in safe, frequent, cheap, and reliable access to space. This is far from what is presently available. To make an analogy, our space transportation system is akin to an airliner that flies only one flight a month to Japan, with one passenger, and with the plane destroyed after each trip. To create a profitable airliner, we need to re-use the shuttle, book more flights, and add more passengers. The same applies to our current space transportation infrastructure. The NSSO asserts that this problem will mainly solve itself; the sheer number of launches required for transporting SPS modules will invigorate the space transportation industry, thereby reducing long-term costs.

NSSO anticipates that with high launch rates and an investment in re-usable shuttles, the cost to orbit of $3000/kg is possible.

5.0 Additional Challenge Areas

Presenting the DOD with a profitable implementation roadmap for SBSP is just the first step in realizing SBSP. An SPS is a huge construction, requiring sophisticated techniques and experts in large structures and new advances in space assembly. Its photovoltaic power generation and microwave power transmission requires advances in solid state electronics, optics, and thermodynamics. In addition, non-technical aspects of international SBSP need to be addressed, such as the public’s concerns and international policy.
5.1 Space Assembly

The current problem with space assembly is that orbital operations with a large number of space operators and sustaining engineers on the Earth are extremely costly. Also extremely costly, is the initial and recurring cost of transporting, maintaining, and assembling functionally unique and specialized hardware. Using or replacing specialized hardware requires yet more trained manual operation and thus more cost. Unfortunately, even the relatively small International Space Station (ISS) has grossly failed on these points: the ISS has relied almost exclusively on manual space operations, engineering guidance from Earth, and specialized hardware. As such, the operational costs of the ISS have been unnecessarily large.

For the construction of very large space structures (such as SPS), a new architectural concept called intelligent modular systems would reduce the total cost of installing and maintaining structure through the robotic assembly of functionally redundant modules. The concept is simple: make very complex and large systems by assembling a large number of smaller, intelligent, and modular systems. These modules would be functionally redundant, making possible the automated, high-quality and low-cost mass production of the individual system components.

Intelligent modular systems take advantage of a “building block” approach to the assembly of large space structures. Due to advances in solid-state electronics, tens of thousands of identical, mass-produced (and therefore cheap) parts could serve as both solar collector and microwave transmitter for the SPS (SunTower Design). Accordingly, maintenance would be a breeze: modules would be simply brought up to space and replaced, and the highly-automated robotic assembly would make any replacement an entirely automated procedure. This strategy would bring-about a tremendous reduction in the cost of maintaining/installing a SPS.
5.2 Wireless Transmission

The physics of microwave power transmission has been solved, demonstrated, and improved upon over the past thirty years. In 1975, at Jet Propulsion Laboratories, 34 kilowatts of power was beamed to a receiver almost a mile away, at more than 82% efficiency. In 1993, researchers from Kobe University in Japan used a transmitter and receiver on a sounding rocket to demonstrate microwave power transmission in space for the first time. Since then, myriad other microwave power transfer demonstrations have been developed to further investigate the technology. However, two primary goals specific to SBSP need to be further investigated. First, at expected frequencies for SBSP, a very large transmitter (> 0.5km diameter) is required, regardless of the amount of power transmitted. Although the physics and technology has been solved, no one has yet tested and built the actual-size microwave transmitter for SPS. Secondly, although electronic beam steering has made the microwave beam precisely-controllable, further demonstration and testing needs to be performed at orbit-distances.

5.3 Public Concerns

The two primary public concerns are safety and the possible weaponization of the microwave beam. Both of these concerns are entirely unfounded and show a basic lack-of-understanding of the principals of SBSP. Longitudinal FCC studies have established a safety standard for human exposure, placing any standing in the...
exact center of the SPS microwave beam to be well within those safety limits. In terms of solar radiation, this would be about the same amount of radiation you would receive on a cloudy day.

Without sending a vastly different satellite into space (certainly not microwave), the weaponization of the microwave beam is also not possible. For wireless power transfer, it is necessary that the microwave beam is diffuse and does not converge to a point. In other words, the physics of proper microwave power transmission prevents it from working as a weapon.

To prevent these two misconceptions from damaging the progress of SBSP, NSSO has outlined the challenge to raise the public’s awareness and understanding of SBSP through education. Whether it is left to the public schools, or to the media, it is strikingly apparent that SBSP is not a presently well-known idea. For example, how is it that nuclear fusion is well understood in nearly every home, while SBSP is known only to science-fiction readers and academics? Current progress would indicate the opposite: nuclear fusion is science-fiction, and SBSP is realizable.

NSSO recognizes that failure to create interest and raise public awareness will continue to result in a lack of funding and support for SBSP. If the American people can excited at the prospect of SBSP, then the possibilities are endless.

5.4 International Policy

Fortunately, no outright international policy currently exists to prevent the development of SBSP. To foster international relations and create new international policy in the domain of SBSP, the NSSO recommends something similar to the International Civil Aviation Organization’s (ICAO) role in facilitating safe international travel. We need an internationally recognized organization to form agreements, obtain permissions, and generate cooperation, especially around the equatorial regions, where most SPS rectennas will be located. These agreements should address liability, indemnity, licensing, tech transfer, frequencies, and other legal and regulatory requirements for SPS-related power transfer.
With growing interest and international cooperation, it will then be in the world’s best interests to create the government/commercial partnerships and relationships needed for this concept to succeed.

6.0 Conclusion

The DOE and NASA studies were a grandiose vision for the future of SBSP. With a limitless amount of solar-power satellites in orbit, there would be no lack of energy on Earth. Unfortunately, this goal has always been stymied by unachievable initial costs, mostly due to transportation expenses. The NSSO study, however, took a smaller approach, and decided to find a practical and well-funded customer in the shortest amount of time: the DOD. With current technology and some investment, the NSSO concluded that $1/Kw can be produced from SBSP; a ridiculous price elsewhere, but a perfect source for DOD’s overseas operations.

However, winning the DOD as a customer of SBSP is just the first step of many toward achieving the full potential of space-based solar power. There needs to be changes in public perception, advances in wireless power transfer and solar collection, and the formation of international alliances and cooperatives. In addition to those challenges already outlined, there needs to be much more. Because, even though the DOE and NASA’s vision of SBSP may seem grandiose, that is because they ultimately recognize the utopian potential in internationally shared space-based solar power.
7.0 Glossary

**Geostationary Earth Orbit (GEO)** – Is an orbit that is fixed directly above the Earth’s equator. When a satellite is in GEO, its period is identical to the rotational period of the earth. Accordingly, the satellite will appear stationary to a fixed observer on the Earth.

**Microwave Power Transmission (MPT)** – A highly-efficient form of wireless power transmission that is typically used at a frequency of 2.4 GHz, within the “microwave range” on the electromagnetic spectrum. Microwave Power Transmission is currently the favored method of long-distance power transfer because of their highly efficient, long distance, and completely safe operation. To illustrate, microwave power transmission yields an efficiency of about 90%, while the internal combustion engines yield an efficiency of only about 20%. In addition, a low-intensity microwave beam has been tested to be completely safe. Accordingly, MPT is most suitable for the power transfer from solar power satellites.

However, the size of the microwave transmitter is relative to the amount of power it can produce. In addition, the receiver must be about 10 times the area of the transmitter. Accordingly, for very large MPT systems, very large transmitters and even larger antennas must be built.

**Photovoltaic Cell** – A device that converts solar energy into electricity by the photovoltaic effect.

**Rectenna** – Rectifying antenna. A traditional antenna, coupled with rectifiers, for the purpose of converting alternating-current electromagnetic radiation into direct-current. Rectennas are primarily used for wireless power transfer.

**Concentrated Photovoltaic (CPV)** – A device that uses a large parabola of highly reflective mirrors to reflect all sunlight onto a given focal point. When the device is oriented correctly, a tremendous amount of solar energy converges onto the focal point, providing power to a specialized photovoltaic cell that is capable of converting tremendous amounts of sunlight into electricity.

Concentrated Photovoltaic has advantages over several other types of solar power generation because it is made with cheap and lightweight materials, while boasting a power output that rivals that of its purely photovoltaic counterpart. With light mass and cheap materials, CPV makes an ideal choice for solar power generation in space.
8.0 References


