



SPACE-BASED SOLAR POWER: A NEAR-TERM INVESTMENT DECISION

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The concept of space-based solar power, also referred to as solar power satellites (SPS), has been evolving for decades. In 1968, Dr. Peter Glaser of Arthur D. Little, Inc. introduced the concept using microwaves for power transmission from geosynchronous orbit (GEO) to an Earth-based rectifying antenna (rectenna). Since then, technology has advanced on several fronts to remove some of the technological and economic barriers to practical full-scale implementation. U.S. decisionmakers are now facing a pivotal moment as several countries continue to invest in this promising, game-changing technology. This paper discusses the history of SPS, a few leading innovators, key functional components, and market applications. Ultimately, the United States must decide whether and how to invest in SPS to optimize the various operational, competitive, and societal benefits that this type of application offers to commercial, defense, and civilian markets.

Background

The sixth mission of the U.S. Air Force's X-37B experimental space plane was launched in May 2020. Among its payloads, it carried an experimental solar power module from the Naval Research Laboratory (NRL) intended to demonstrate power generation and conversion to radio frequency energy that could be transmitted across long distances.¹ This is the latest development in a long history of efforts to realize the potential of large-scale collection of solar power in space and the delivery of that power to distant users.

The study of SPS has been conducted at government agencies, universities, and other research organizations in the United States for more than half a century. But the concept has yet to reach fruition because the technology is challenging and efforts to develop it have been inconsistent and minimally funded. Despite the current NRL test and other pockets of activity, little is being done in the United States to initiate a series of flight experiments that would lead to demonstration of a complete system including on-orbit and ground components, eventually scaling up to operational size.

Overview of SPS Research

Although the United States was a pioneer in this technology, its small and sporadic projects could become overshadowed by increasing international efforts. Japan has been keenly interested in SPS for a long time, and China, Russia, India, South Korea, and other countries have become active in pursuing SPS technologies.² If proven, SPS systems could have dramatic

implications for all sectors of space activity and yield technology dividends to a variety of terrestrial markets, especially energy and transportation.^{3,4} Ultimately, the race to become a leader in space-based solar power could serve long-term geopolitical interests as various countries compete to dominate cislunar space. Alternatively, leading space-based solar energy innovators could work *together* to address global energy security and greenhouse gas emissions challenges.

United States SPS Research. The *Naval Research Laboratory (NRL)* designed the world’s first satellite powered by solar cells—Vanguard 1, which was launched in 1958. Since then, NRL has been involved in a variety of solar power research, including the following SPS-related projects:

- ▶ *Photovoltaic Radio-frequency Antenna Module (PRAM).* The first orbital SPS experiment was launched on the X-37B space plane in May 2020. It featured a 12-inch square photovoltaic module to test the viability of space-based solar power systems by converting sunlight to microwaves outside the atmosphere and analyzing the energy conversion process and resulting thermal performance.
- ▶ *Lectenna.* A light-emitting rectifying antenna converted a wireless network signal into electric power. This International Space Station experiment was conducted during February 2020.
- ▶ *Power Transmitted Over Laser (PTROL).* NRL conducted a successful demonstration of a land-based power beaming system using an infrared laser during 2019.

The *Air Force Research Laboratory (AFRL)* is focused on ensuring mission success by finding power solutions for forward-operating bases. To support this goal, AFRL is developing an SPS transmission capability using high-efficiency solar cells. The *Space Solar Power Incremental Demonstrations and Research (SSPIDR)* intends to capture solar energy in space and precisely beam it. Northrop Grumman is partnering with AFRL and was awarded a \$100 million contract.

The *Department of Defense (DOD) National Security Space Office (NSSO)* conducted a 2007 study titled *Space-based Solar Power as an Opportunity for Strategic Security*. It concluded that the United States should begin a coordinated national SPS program.

NASA has a long history of SPS research dating back to 1975, when *NASA* and Raytheon used satellite components to send a wireless microwave electric signal across a mile-wide valley in Goldstone, California. Other examples over the past 50 years include:

- ▶ Mid- to late-1970s “Energy Crisis” era. Collaboration with the *Energy Research & Development Administration (ERDA)* (later reorganized to the Department of Energy) included SPS as part of alternative energy studies.
- ▶ 1995-1996. *A Fresh Look at Space Solar Power* updated the findings of previous *NASA* work on this topic. The study examined whether SPS could be a viable alternative to terrestrial electrical power, including economic, environmental, and safety perspectives.
- ▶ 2012. *NASA Innovative Advanced Concepts (NIAC)* study examined various concepts and supported Solar Power Satellite Arbitrarily Large Phased Array (SPS-ALPHA), including detailed studies of technology readiness and economic viability. The concept included individually aimed thin-film mirrors, typically in geosynchronous Earth orbit (GEO), which would capture and convert sunlight into a coherent microwave beam and transmit power to Earth or other destinations in space.

Leading International SPS Innovators. Both Japan and China appear to be international leaders in SPS.

The *Japan Aerospace Exploration Agency (JAXA)* has consistently included SPS in its space planning⁵ and has made steady research investments in SPS since the late 1990s, including two conceptual designs:

- ▶ *SPS2000* - a low Earth orbit (LEO)-based constellation providing constant power to ground stations
- ▶ *SPS2004* - a GEO-based satellite with rotating solar collection mirrors

In 2014, JAXA announced a technology roadmap to build orbital solar power stations with a combined capacity of 1 GW by 2030. The objectives are to enhance the accuracy of the microwave beam-pointing control, increase the conversion efficiency from direct current (DC) power to microwaves (in space); increase the conversion efficiency from microwave to DC power (on the ground); and reduce the size and weight of the electronic modules.

China intends to become a global SPS leader and views SPS as a strategic imperative to shift from fossil-based energy and foreign oil dependence. China's SPS strategy is dual use—military and civil. SPS milestones include:

- ▶ 1990: Interest in SPS initiated
- ▶ 2010: Publication of an SPS roadmap
- ▶ 2019: Establishment of the first state-funded prototype SPS program
- ▶ *by 2025*: Demonstration of a 100 KW system in LEO
- ▶ *by 2030*: Plans for a 300-ton MW-level space-based solar power station^{6,7}

Other International SPS Innovators. Russia, Europe, and India are also working to advance their space-based solar projects.

Russia announced during the late 1980s that it plans to use satellites to collect solar energy and beam it back to Earth.⁸ Rather than microwaves, Russia's plans evolved to use infrared lasers spread across the area of the panels, with the intention of combining their radiation to create a powerful-enough laser beam to transfer the electricity to Earth.⁹

The *European Union* is funding long-term research with potential delivery of an operational system many years away. *Solspace* (scheduled to run from December 2020 to November 2025) involves large, lightweight reflectors redirecting sunlight onto terrestrial utility-scale solar power farms.¹⁰

India has been investigating SPS concepts for many years, seeing the technology as critical for “large-scale societal missions” as part of a “World Space Vision 2050.”¹¹

Market Applications: Power Beaming in and from Space

Users of rechargeable consumer electronics such as cell phones are already familiar with wireless power transmission using a near-field method such as resonant coupling. SPS involves far-field microwave energy transfer and can be achieved at long distances using precisely aimed microwaves or laser beams. The potential user community for space-based wireless power transmission can be described in three general categories:

- ▶ Terrestrial electric power providers

- ▶ Terrestrial electric power users with high demand or in remote locations (e.g., institutional users such as military bases, isolated towns, large mining and manufacturing operations, electric rail transportation systems)
- ▶ In-space infrastructure (e.g., satellites, space stations, lunar bases)

Terrestrial Electrical Utility Markets. Early studies, including one by NASA and the Department of Energy (DOE) in the late 1970s,¹² focused overwhelmingly on serving the terrestrial power grid. This remains an important objective as demand for electricity continues to grow worldwide,¹³ although serving the other two categories of users may become technically and economically feasible much sooner. In the terrestrial power grid, SPS would compete with a variety of entrenched and relatively inexpensive energy sources, including fossil fuels and renewables. In populated areas, traditional sources can deliver power to consumers at a price of a fraction of a dollar per kilowatt. Some experts we spoke with believe SPS eventually can achieve a competitive price point, but the timeframe may be measured in decades. When that time comes, SPS may be capable of supplying the power grid with renewable energy that is not limited by day/night cycles or weather.

Specialized and High-Demand Terrestrial Applications. Some types of terrestrial users have special needs that incur much higher costs. Nowhere is the cost of electricity higher than in forward-deployed military bases, because it is measured in human lives and combat effectiveness as well as dollars. These bases are powered by generators that require liquid fuels to be trucked through potentially hostile territory, and fuel convoys have been frequent targets of attack.¹⁴ For example, estimates for the cost of fuel deliveries in Operation Iraqi Freedom in the mid-2000s ranged from \$15 to hundreds of dollars per gallon.^{15,16} What’s more, those estimates didn’t include the cost of casualties. As of November 2007, “Approximately 80 convoys traveled continuously between Kuwait and Iraq destinations, all protected by uniformed forces. This degrades combat capability, resulting in real costs, even if not attributed to the supplies themselves.”¹⁷ A 2009 study documented increasing dependence on fossil fuels in wartime, and its contribution to ever-higher casualty rates. The study highlighted the link between improvised explosive devices (IEDs) from insurgent groups, which caused nearly two-thirds of coalition deaths in Iraq and Afghanistan, and fuel transportation activities.¹⁸

Apart from the military, there are many current and prospective electricity users that could benefit from beamed power from space. Isolated communities could end dependence on fuel-consuming generators. On-demand power beaming from orbit could replace or augment intermittent ground-based renewables. Heavy power users of the future could reduce or eliminate their dependence on the grid or dedicated power generation capabilities by leasing satellite beams. Such users may include large industrial facilities, electric rail systems serving regional or national routes, and power-hungry desalination plants that have been increasing in number and capacity worldwide.^{19,20}

Space-to-Space Power Beaming Applications. Satellites and facilities in cislunar space may be the first customers of beamed power as it becomes available. On-board solar arrays have powered spacecraft ranging in size from a couple of kilograms to the approximately 400,000-kilogram International Space Station, which produces over 100 kilowatts of power. The cost of that power is high, and the systems to produce it are a substantial portion of the mass of the spacecraft. Projections for the growth of cislunar activity point to commensurate growth in demand for power, and some installations could require power levels in the multi-megawatt range, far higher than any power system deployed in space thus far. SPS systems could become one possible solution to address that demand.

Wireless power transmission could serve the needs of NASA, other national space agencies, and companies that are currently investigating lunar mining, especially the harvesting of ice deposits at the lunar south pole. The energy-intensive work of extraction and processing could be powered by SPS systems in lunar polar orbit. Alternatively, the sun-drenched peaks above near-polar craters could host solar collectors that beam power into the permanent darkness below, allowing easy redirection of the power to where it is needed.

Meeting the Technical and Operational Challenges

According to a 2011 study by the International Academy of Aeronautics, “There are no fundamental technical barriers that would prevent the realization of large-scale SPS platforms during the coming decades.”²¹ SPS technology maturation and adoption will depend upon investments in research and development, prototyping, and flight demonstrations. Concurrently, supportive development policies and favorable economics for durable applications will be needed to bring the concept to fruition.

Collection of solar power in space and transmission of power across distances are both demonstrated technologies. The technical questions that need to be answered have to do with whether the system can be scaled up sufficiently and whether transmission across the long distances of cislunar space and through Earth’s atmosphere is safe and practical.

Skeptics of SPS systems have pointed to a litany of challenges that cast doubt on technical and economic feasibility. At the top of that list is the cost of access to orbit because the mass of an SPS system is likely to be very large, requiring many launches. Other challenges include the cost of space-rated components, the amount of extra-vehicular activity required for assembly, the ongoing operations and maintenance costs, and mitigation of environmental effects.

Over the years, researchers in the United States and abroad have proposed many architectural designs that attempt to address these challenges.²² Early research in the 1970s focused on power beaming concepts involving large, monolithic transmitter and receiver structures. The 1990s saw a move toward structures that were at least partially modular, still using a common backbone. More recently, the focus has been on completely modular structures that reduce costs and increase flexibility.²³ Along the way, technical advances inside and outside the space industry have worked in favor of the feasibility of these design concepts:

- ▶ Launch opportunities are becoming more available and less costly
- ▶ Solar cell efficiency has improved dramatically since SPS studies began
- ▶ Mass production of modular spacecraft components, accompanied by interface and interoperability standards, is becoming a reality
- ▶ Very large commercial space projects (e.g., constellations of thousands of satellites), requiring multibillion-dollar investments from multiple sources, are now considered achievable
- ▶ The use of robotics for assembly and operations has become a credible substitute for space-walking astronauts
- ▶ Harvesting of lunar materials is being considered seriously, opening the possibility that not all of the mass of SPS components needs to be lifted from Earth

A commitment to SPS development should not be judged in isolation from other space efforts. If spacefaring nations and businesses plan to fulfill other missions by pursuing technologies applicable to SPS (e.g., large launch vehicles, advanced space robotics, assembly of large space structures, and exploitation of lunar and asteroidal materials), this investment in new capabilities will advance SPS development.

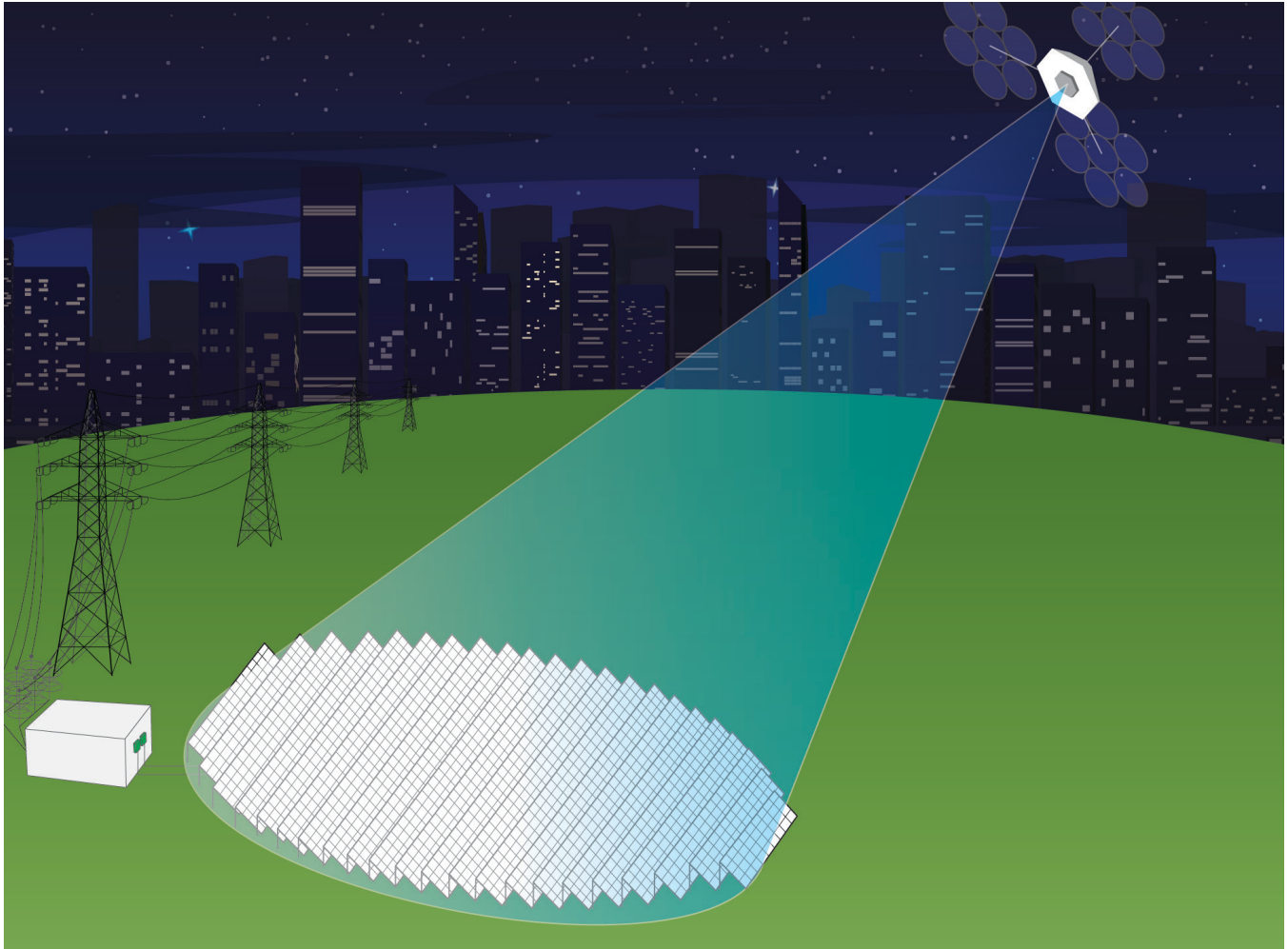


Figure 1: Artist's concept of a rectenna, a ground site that receives the microwave power transmission from a solar power satellite and converts it for a utility grid or other users.

Safety and Environmental Concerns. Power beaming systems will need to address safety and environmental concerns, both real and perceived. Although low-level microwaves are ever-present in modern society due to telecommunications infrastructure, high-power density microwave beams can cause serious harm to the environment, animals, people, and aviation operations. SPS operators will be responsible for complying with all safety, environmental, health, and interference protection practices, laws, and regulations. The standards organizations Institute of Electrical and Electronics Engineers (IEEE) and American National Standards Institute (ANSI) have established and approved exposure criteria and limits to protect against adverse health effects across various frequencies.²⁴ Ensuring that the power density is low enough (the maximum-allowable microwave power level has been set to 10 W/m^2 in most countries) to avoid any harm typically involves consideration of tradeoffs between the rectenna area size and power output. Perhaps someday, higher power density systems could be supported with appropriate safety regulations and protocols in place. However, for now, the IEEE and ANSI peak power density criteria provide a limiting factor on SPS and this is one reason why terrestrial rectenna sizes are rather large – often one or more kilometers in diameter.

Key Functional Components

Figure 2 provides an overview of the key functional components for SPS. Many SPS architectures have been proposed over the years. Most involve some combination of concentrators, solar cells, and either laser or microwave transmission.

Solar collection (Figure 2, left side) can be optimized with concentrators such as mirror assemblies. There is also considerable research in solar capture technologies:

- ▶ **Flexible thin PV film.** Optimized for low mass, low cost, and high production. Flexibility promotes deposition on lightweight inflatable structures needed for packaging large arrays in launch vehicles.
- ▶ **High-efficiency, multi-junction PV.** Significant improvements have been achieved over the years. Recently demonstrated efficiency of 39.2% under natural sunlight conditions.²⁵
- ▶ **Quantum dots.** Although this new technology’s power conversion efficiency is around 16.6% today, it could someday, theoretically, yield conversion efficiencies up to 66%, compared to 31% for today’s high-efficiency solar cells.^{26,27}
- ▶ **Perovskite solar cells.** These cells emerged in 2012 and have attracted considerable global R&D attention. Power conversion efficiencies have rapidly reached over 20%. Fabrication cost could be less than silicon PV cells. For the longer term, challenges remain regarding the material vulnerability to environmental stresses.²⁸

Wireless power transmission (Figure 2, middle) involves either microwave or laser technologies. Laser power beaming has proven to be challenging because laser light can be blocked by cloud cover. Lasers are more suitable for space-to-space transmission where there are no concerns for atmospheric interference. By comparison, microwave transmission appears to be more practical for space-to-Earth applications because this type of directed energy is unimpeded by cloud cover in a wide frequency range. Microwave transmission involves:

- ▶ **Convert and transmit.** A microwave power generator using a transmit antenna beams microwave energy.
- ▶ **Rectenna or rectifying antenna.** (Figure 2, right side). The receiver station includes an antenna to capture the microwave beam and converts RF energy to usable DC electrical energy.

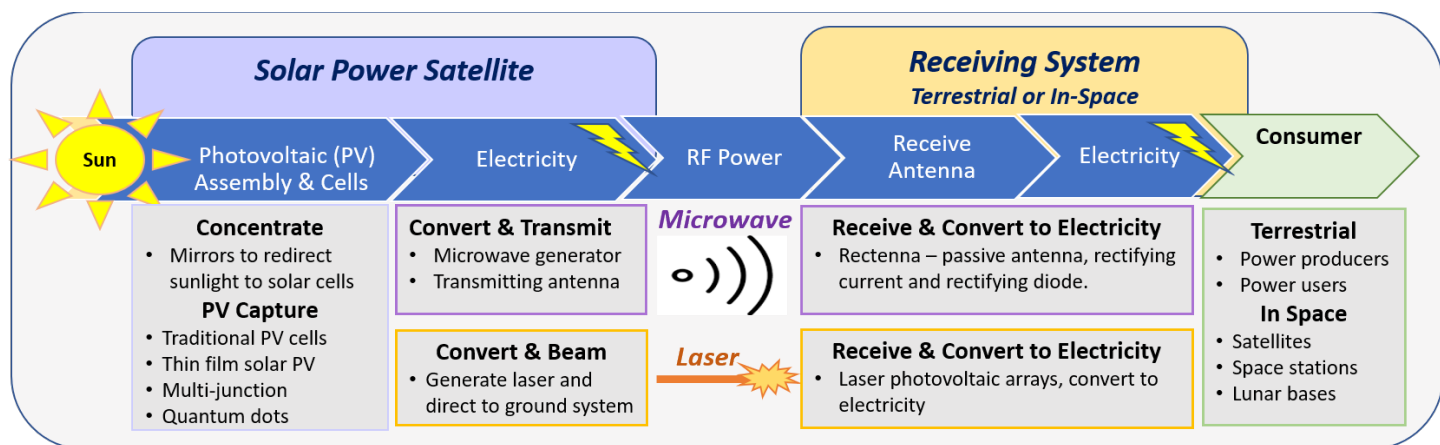


Figure 2: SPS functional components for microwave or laser transmission from GEO.

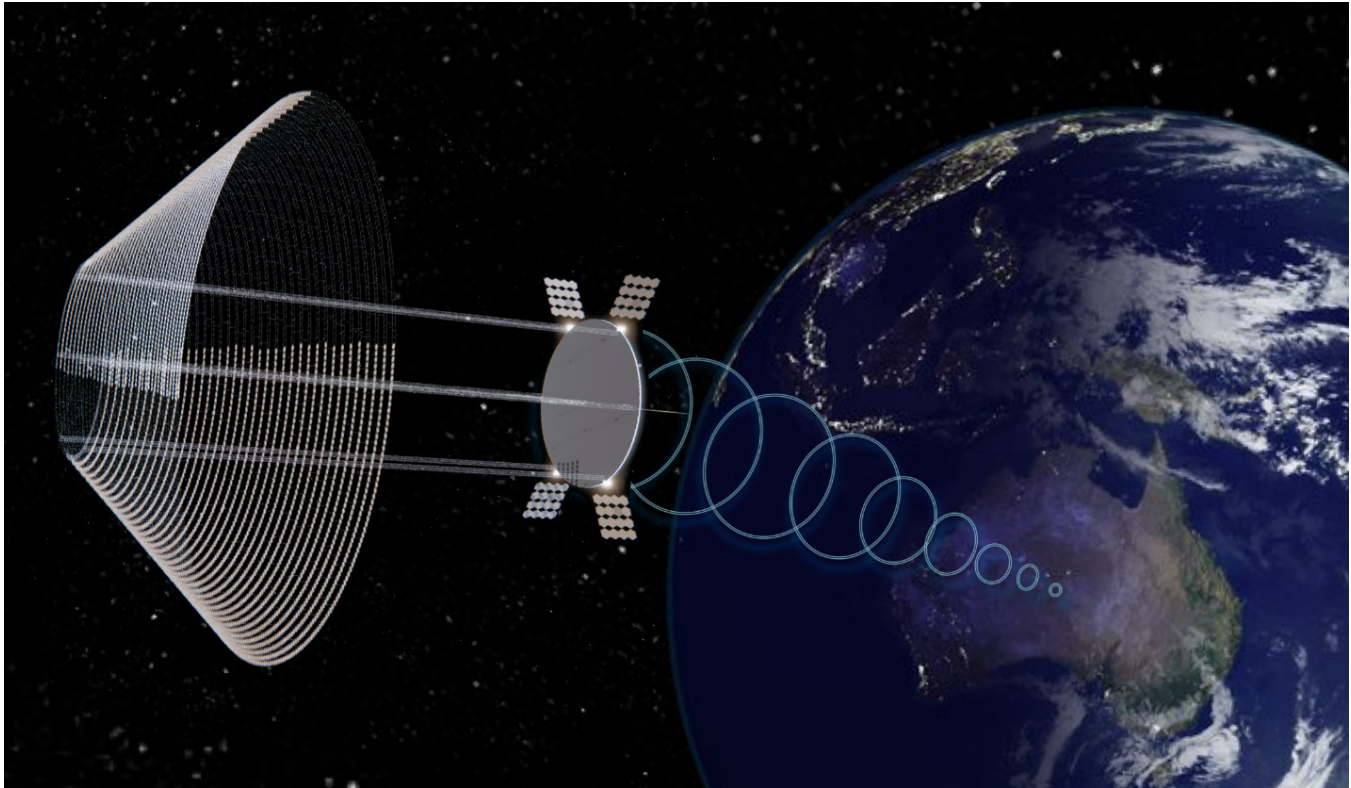


Figure 3: Highly modular SPS-ALPHA Mk-III space solar power system concept with light-weight structure and heliostat reflector array, transmitting power to Australia. (Image courtesy of John C. Mankins)

Various SPS architectures involve combinations of key functional components. All possible SPS designs must deal with the unique physical and economic challenges of the space environment. Within this unique trade space, new architectures are leveraging advances to address, for example: damaging high- and low-energy particle radiation on the PV cells; material mass efficiency requirements to ensure adequate mechanical support and launch mass restrictions; optimal PV cell efficiencies; and new materials such as carbon fiber composites. Additionally, thermal pathways to dissipate waste heat remain a challenge for PV cell design. However, there is ongoing research at the Department of Energy’s (DOE) National Renewable Energy Laboratory and elsewhere to improve the efficiency of crystalline silicon solar cells which can reduce their temperature.

Spin-off Benefits. Advances in key functional components address a range of sectors— including terrestrial energy, defense, and mobile applications. Power beaming offers flexibility, allowing for a range of applications where the operator may want to “untether” a device from the power source. For instance, beaming microwaves or laser energy to unmanned aerial vehicles (UAVs) and other autonomous systems could increase operating time. Power beaming could also recharge Internet-of-Things devices, electric vehicle charging stations, auxiliary power for vehicles, and mobile communication terminals. Research related to power beaming could also be applied to the advancement of directed energy weapons for military applications.

Opportunity for Decisionmakers

The debate over SPS at times has included extreme positions. Proponents have portrayed it as the smartest, most comprehensive energy solution available, while detractors have seen it as an insanely expensive scheme that will never work. As is typically the case in such arguments, the reality lies somewhere in between – but no one knows exactly where because we have yet to invest sufficient resources to find out.

SPS will not be a quick, easy, or comprehensive solution. However, many other countries are moving in this direction, so the U.S. government must decide whether the nation should attempt to lead the pursuit of this potential game-changer, collaborate with others, or pass up this opportunity to focus instead on other energy solutions.

U.S. government forays into SPS investigations peaked in the late 1970s (the aforementioned NASA-Department of Energy study) and late 1990s (the NASA Fresh Look study).²⁹ In recent years, there has been growing interest in parts of the U.S. national security community.³⁰ Meanwhile, traditional barriers to SPS development— launch costs, the feasibility of robotic assembly and maintenance, and the need for high-volume production of modular components—have been overcome, or will be in the next few years if they continue on their current path.³¹

U.S. decisionmakers will have an opportunity during the next presidential term to establish the role of the United States in this potentially disruptive technology. If SPS can develop into a major component of orbital infrastructure, and someday contribute an additional source of renewable energy to users on Earth, the United States will want to be at the forefront of high-capacity power beaming in all its applications rather than become dependent on others for the technology and services they provide.

In addition to small-scale tests such as NRL’s on-orbit power module experiment, many other space- and ground-based elements must be tested in realistic operational environments, including high-volume component manufacturing, affordable payload processing and launch options, on-orbit robotic assembly and maintenance, microwave beaming at high power levels across very long distances, and design and operation of ground receivers. A coordinated and sustained program leading to large-scale demonstration of a complete system is a logical follow-on to current experiments. In the meantime, the U.S. government could adopt a portfolio management approach to encourage:

- ▶ Completeness of vision surrounding current government programs
- ▶ Efficient resource management to avoid redundancies and to encourage judicious prioritization of critical projects
- ▶ Collaboration with international partners to leverage existing SPS competencies

An interagency working group with key interests represented could provide a well-defined strategy and rigorous assessment approach for the various projects.

Government and private sector investments in developing and deploying SPS likely would be spread over the next two to four decades, during which time cislunar activity is expected to grow dramatically while on Earth, trillions of dollars in new electricity-generating capacity will be required.³² So far, in a half-century of study of the SPS concept, the U.S. government’s on-again, off-again research funding has averaged only a couple of million dollars a year. A more coordinated and consistent investment may attract partners in the private sector, including some large enterprises not traditionally associated with space development (e.g., in the energy, transportation, and robotics industries). Decisionmakers must determine if there is a reasonable expectation of long-term societal benefits through government involvement beyond the current level of effort.

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