Solar Power in Space?

Peter Garretson, Lieutenant Colonel, USAF

Whoever takes the lead in the development and utilization of clean and renewable energy and the space and aviation industry will be the world leader.

—Prof. Wang Xiji, Chinese space program pioneer

Space-based solar power (SBSP) is a concept for a revolutionary energy system. It involves placing into orbit stupendously large orbital power plants—kilometers across—which collect the sun's raw energy and beam it down to where it is needed on the earth. In theory, SBSP could scale to meet all of humanity's energy needs, providing virtually unlimited green, renewable power to an energy-hungry world.

Most renewable energy schemes suffer from intermittency and low energy density, requiring vast amounts of land and extensive storage as well as fossil fuel backup systems. Not so with SBSP systems. When placed in orbit where the sun shines constantly, they can deliver stable, uninterrupted, 24-hour, large-scale power to the urban centers where the majority of humanity lives. A network of thousands of solar-power satellites (SPS) could provide all the power required for an Earth-based population as large as 10 billion people, even for a fully developed "first world" lifestyle but without the environmental downsides of nuclear or coal.

Should space-based solar power have a role in the US grand strategy for space? Should Airmen advocate for a US program in SBSP? Depending on your viewpoint, SBSP is either the most important space project of our generation—critical to securing American long-term interests and requiring the advocacy of Airmen—or a fool's errand, an impossible dream threatening to divert valuable resources from where they are most needed today.

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Some consider SBSP an embarrassment deserving contempt and active suppression, a proposal from which Airmen should steer well clear. Airmen must seriously consider advocating for SBSP, because today there are several space-faring states with stated national objectives and active interest in developing this technology. Two very capable space-faring states already have funded programs. The implications are vast. The advocacy should consider the scope and feasibility of SBSP and the desirable space strategy for the concept. Additionally, any argument must recognize both the concerns of the detractors and international activity surrounding SBSP while presenting the opportunities and recommendations for the future of the idea.

Scope and Feasibility

> *As of 2010, the fundamental research to achieve technical feasibility for the SPS [solar-power satellites] was already accomplished. Whether it requires 5–10 years or 20–30 years to mature the technologies for economically viable SPS now depends more on the development of appropriate platform systems concepts and the availability of adequate budgets.*
>
> —International Academy of Astronautics (IAA), 2011

The world needs a constant supply of uninterrupted electrical power to enable and sustain economic growth; power its cities, factories, and vehicles; and provide energy for heating, cooling, lighting, cooking, and desalination. Long term, it is desirable to transition from an energy system based on fossil fuels—an exhaustible resource which alters the composition of our atmosphere with unknown long-term effects on our climate—to a system based upon renewable sources. Many see solar power as the answer, because the resource is so vast and available.

However, traditional solar power has limitations that make it less than a perfect match for our society. It is highly intermittent (only a 20-percent duty cycle) due to weather effects (clouds, rain, dust), and its low density requires vast tracks of land. Worst of all, it is not available at night, requiring vast storage or nonrenewable backup systems. Space-based solar is an innovation designed to retain the advantages of traditional solar power while sidestepping the disadvantages.

The basics of the idea are quite simple. Rather than cope with the unpredictability and intermittency of solar power on the ground, go where the sun always shines.

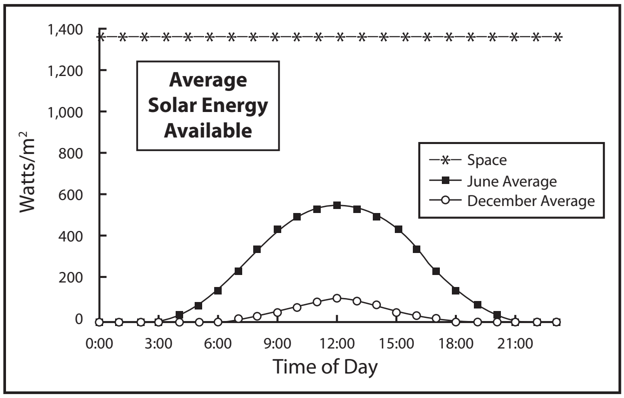

Figure 1. Solar energy available and captured (National Security Space Office, Space-Based Solar Power, 2007, 32.)

In geostationary orbit (GEO), the sun shines constantly and is 36 percent stronger, allowing a solar array to collect almost 10 times the amount of energy as the same array installed at mid latitude on the ground (see fig.1). Power can then be transferred (beamed) directly to where it is needed. The technologies to do this are not magic or unfamiliar—they are the same elements used every day to emplace, power, and communicate with every existing satellite. Building the SBSP system would rely on the same familiar solar cells, radio transceivers, and rockets to propel them to GEO, only assembled on a grand different scale. In a mature system-of-systems, multiple solar-power satellites would reside in geostationary orbit, each collecting vast amounts of power and transmitting it through active electronic beam steering, like routers in a vast orbiting power internet.

While appearing to hover above a particular location, each SPS could service multiple markets, providing power on demand to urban centers or remote locations. For example, a single satellite south of Baja California could service markets across most of North and South America; a satellite over the Indian Ocean could service markets as far apart as Africa and Indonesia, and from Diego Garcia to as far north as Russia.[1]

Power in this system-of-systems would be transmitted using a technique called retrodirective phased array, where an encrypted pilot signal from the ground handshakes with the satellite's active electronic beam-steering system to link transmitter and receiver. The beam itself would be in the ISM band (typically 2.45 or 5.8 GHz), so that it passes nearly full strength through the atmosphere, clouds, and rain. Because of low atmospheric losses (<2 percent), extremely efficient reconversion (>80 percent), and most of all, constant illumination, the beam can be safely kept at an amazingly low intensity (only one-sixth the intensity of sunlight) and yet be significantly more energy productive than a comparably sized terrestrial solar plant. The location and diameter of the beam are predictable and well confined.

Unlike communications satellites—which, because of their small-aperture antennas, cast continent-sized footprints and must be separated by degrees (and thousands of miles) on orbit to deconflict signals—SPSs have very large apertures and therefore can send very narrow beams, allowing them to be spaced much closer together. The beam itself terminates on a receiver called a rectenna, with peak intensity in its center and tapering to nearly nothing at the periphery. The rectenna, about the size of a municipal airport, is a mesh of dipole antennas that capture all the incident energy from the beam. It is nevertheless 80 percent transparent to sunlight, allowing the land beneath to remain available for agricultural uses.

Although composed of simple elements, satellites comprising this system-of-systems would constitute an amazing engineering feat of unprecedented scale and power. Individual SPSs, such as those described as feasible in the November 2011 *International Academy of Astronautics (IAA) Report*,[2] would transmit as much as 1–10 gigawatts (GW) of constant energy as compared to a typical nuclear power station output of 0.5–1.0 GW. A gigawatt could light 750,000 homes. The architecture currently favored would consist of a large, gravity-gradient-stabilized truss structure supporting large sun-facing, ultra-low-mass membrane mirrors that rotate to focus sunlight on a collector/transmitter, itself assembled from thousands of identical "sandwich" modules made of high-efficiency photovoltaic cells on top and Earth-facing phased arrays on the bottom.

The transmitting aperture alone—a phased array—would likely be a kilometer across. The entire multi-gigawatt system might be as wide as seven kilometers across and weigh on the order of 800–1,200 metric tons (mt). Depending on the designed payload size of the launcher, it might require perhaps 480–800 launches of a reusable space plane to erect the system.

The scale of this ambitious project should give the reader pause. On the one hand, in 2011 the United States launched only 18 times to space,[3] and the largest object in space today, the International Space Station (ISS) took years to assemble, has a mass of only 450 mt, and produces only .25 MW of power. On the other hand, the scale is quite modest when compared to that of logistical movement in aviation and shipping. For instance, a major US airport like Atlanta's Hartsfield-Jackson sees nearly 1,350 takeoffs daily and moves 60,000 mt annually.[4] If successful in the market, ultimately thousands of systems could be launched to geosynchronous orbit to supply part or all of the estimated 55-terawatt (TW) power requirement for all earthly energy needs by the year 2100.[5]

Humanity has never contemplated either a space or energy project on such a vast scale or one which would so alter our relationship to the cosmos. It is a space project, an energy project, a transportation project, and an infrastructure project. On a scale of ambition, it is unparalleled. It is the Apollo Project, the Manhattan Project, the transcontinental railroad, the Eisenhower interstate highways, the TVA, and the rural electrification projects all in one.

As ambitious as this vision seems, there is reason to believe it is feasible. According to the *IAA Report*, "There are no fundamental technical barriers that would prevent the realization of large-scale SPS platforms during the coming decades . . . no fundamental breakthroughs appear necessary, and the degree of difficulty in projected R&D appears tractable . . . [and] no fundamental 'show-stoppers' among the required supporting systems [Launch and on-orbit tugs]." The report provides an international roadmap noting that "systems studies are not enough. Technology flight experiments to test critical technology elements and technology flight demonstrations that validate SPS systems concepts to a high level of maturity appear to be essential."

Even if problems of energy and climate were not urgent, or if energy-satisfying substitutes existed, Airmen would still have an interest in highlighting the potential of this technology for two reasons: first, its potentially beneficial effect on US capabilities in space, and second, the fact that other nations are currently pursuing SBSP.

Desirable Space Strategy

Our current *National Space Policy* articulates the top three space-related goals as:

- Energize competitive domestic industries to participate in global markets and advance the development of satellite manufacturing, satellite-based services, space launch, terrestrial applications, and increased entrepreneurship;

- Expand international cooperation; and
- Strengthen stability in space.

It continues by articulating several foundational activities important to the nation:

- Strengthen US leadership in space-related science, technology, and industrial bases. Encourage an innovative and entrepreneurial commercial space sector.
- Enhance capabilities for assured access to space. Develop launch systems and technologies necessary to assure and sustain future reliable and efficient access to space, in cooperation with US industry.
- Develop and retain space professionals. Promote and expand public-private partnerships to foster educational achievement in science, technology, engineering, and mathematics (STEM) programs; embrace innovation to cultivate and sustain an entrepreneurial US research and development environment.
- Strengthen interagency partnerships.
- International cooperation. Strengthen US space leadership. Facilitate new market opportunities for US commercial space capabilities and services, including commercially viable terrestrial applications that rely on government-provided space systems.[6]

SBSP can be seen as a desirable strategy to achieve these national-level goals, consistent with the foundational activities, and with desirable effects for the USAF and the DoD.

Fundamentally, a successful SBSP program would transform our industrial base and competitiveness and be at least as significant for American STEM programs as were the post-Sputnik and Apollo expansions in aerospace engineering. It would greatly expand the role of commercial space, and the effect on assured access and launch would be profound. Its natural confluence of challenges in space, energy, and security offers exciting options to further interagency partnerships between NASA, DOE, DoD, FAA, FCC, EPA, DOC, and DOS. It presents excellent opportunities for the United States to lead in international cooperation.

> *A prophet is honored everywhere but in his own country and in his own home.*
>
> —Luke 4:24

The strategic case for SBSP was most recently articulated in 2007 when the National Security Space Office (NSSO, the executive agent for space), published a report titled *Space-Based Solar Power: An Opportunity for Strategic Security*. The report summarized the findings of a study group of world-class experts who concluded that space-based solar power was technically feasible and recommended the United States initiate a new national program. It further stated that if the United States began a coordinated national program to develop SBSP, it should expect to find that "broad interest in SBSP exists outside of the US government, ranging from aerospace and energy industries, to foreign governments such as Japan, the EU, Canada, India, China, Russia, and others." It also warned, "While the best chances for development are likely to occur with US government support, it is entirely possible that SBSP development may be independently pursued elsewhere without US leadership."[7]

> *China has acquired sufficient technology and had enough money to carry out the most ambitious space project in history. Once completed, the solar station, with a capacity of 100 MW [megawatts], would span at least one square kilometre, dwarfing the International Space Station and becoming the biggest man-made object in space.*
>
> —Prof. Wang Xiji, 2011

Most Airmen would like to see the United States lead in space and maintain its preeminence in technology. Adapting Billy Mitchell's dictum about airpower,[8] "space power is anything a nation can do in space," it is inescapable that if a nation can build a solar-power satellite, it can do a lot more in space than the United States is doing today. SBSP presents our nation a desirable strategy to develop underlying technologies that will determine future preeminence in space.

Were the United States to succeed in such a technological endeavor, it would offer reduced dependency on unstable foreign sources of energy and an opportunity to become a net supplier for a vast and expanding market (both in energy and launch). It may well become an industry of comparable size and value to the aviation or automotive industries, vastly expanding the nation's capabilities and market share in space while offering unique opportunities for international partnerships.

Strategically, a national SBSP program would be of enormous benefit to American security interests. A strategic source of energy that transcends our fossil fuel regime would expand US foreign policy freedom of action, making it less dependent on unstable foreign energy sources. It would curtail financing of ideologies that do not share our values of democracy and human rights while offering an inspiring solution to global climate change.

Pursuing an exportable energy system that could actually solve the problems of global energy security, scarcity, climate change, and sustainable development offers the possibility of proactively reducing the number of potential contingencies where the US military might be called upon to respond. Additionally, being seen as a good-faith supplier of such global public good and inspiring vision for humanity contributes to US legitimacy and lowers the cost and difficulty of maintaining US leadership globally.

A national program in SBSP would also help the DoD and State Department in their missions to secure global partner and US interests, promoting stability and security across the global commons in general. It would promote international collaboration and engagement with nontraditional partners in the space domain.

Tactically, America's national security space enterprise strongly leverages dual-use capabilities and would benefit in several ways from a national program in SBSP. First, the USAF and the DoD would benefit from an increased population of aerospace engineers working on an ambitious, advanced project. A national program in SBSP would necessarily create new high-tech jobs in the United States, inspire America's youth to STEM career fields, and help combat a rapidly shrinking technical and industrial base.

Benefits to the DoD include reenergizing a range of space industries, which would directly contribute to national competencies in space access, maneuver, and on-orbit capabilities (including power) that expand freedom-of-action, any of which might offer the potential to lower costs to the DoD for essential products and services that support its missions and users.

> *Only the small secrets need to be protected. The large ones are kept secret by public incredulity.*
>
> —Marshall McLuhan

With such obvious benefits for the nation and so many potential stakeholders, one would think it easy to move forward, but it is not. SBSP advocates have failed to place the idea on the national agenda. Despite addressing multiple audiences, they have failed to convince the most influential decision makers. While scattered programs which contribute to the essential competencies exist across NASA, the DOE, and the DoD, the sum total of America's commitment to SBSP is one very small grant by the NASA Institute for Advanced Concepts (NIAC) to a single US researcher for a mere $200K.[9]

The Detractors

There is nothing more difficult to take in hand, more perilous to conduct, or more uncertain in its success, than to take the lead in the introduction of a new order of things. For the reformer has enemies in all those who profit by the old order, and only lukewarm defenders in all those who would profit by the new order, this lukewarmness arising partly from fear of their adversaries . . . and partly from the incredulity of mankind, who do not truly believe in anything new until they have had actual experience of it.

—Niccolo Machiavelli, 1532

Consider that in the same month the prestigious International Academy of Astronautics released its study concluding that "solar-power satellites appear to be technically feasible as soon as the coming 10–20 years using technologies existing now in the laboratory . . . [and] economically viable solar-power satellites (SPS) appear achievable during the next 1–3 decades," a senior review panel—which included at least two former USAF chief scientists—removed any mention of space-based solar power from the draft "Air Force Energy Horizons" report, a document intended to be visionary and covering the same period of time. (See author's correction at end of article.)

The difference between the evaluations of the IAA and the USAF Energy Horizons does not portray how divided the community is or how vehement is the opposition to even due-diligence exploration of the concept.[10] How controversial is it? No other project has continually animated a small group of disempowered advocates who find the vision inspiring nor drawn the outright ire of seasoned technical professionals, as this quote from one Air Force Research Laboratory scientist demonstrates: "AFRL decided for good reason not to further support SSP. . . . A former AF Chief Scientist . . . chastised

AFRL saying it was one of the dumbest ideas he's ever seen . . . A [senior HQ NASA official] prohibited all NASA centers from any further involvement with SSP . . . there are so many other crucial areas requiring attention. . . . This is a concept the Air Force can do without, especially considering the lean years ahead."[11] And another, "If the government, especially the USAF spends one thin dime on this, I'll be a GAO whistleblower. . . . They need to avoid this like the plague, or I will surface their incompetence to management . . . or high enough that I'd find some sane person that understands. It always looks good to the clueless and uninformed."[12]

The individuals who oppose SBSP are of unimpeachable technical ability and serve the nation with distinction. They are protectors of Air Force credibility. Their arguments are sophisticated and based on a lifetime of experience and ought to rightly command attention and respect. They take the position that extraordinary claims require extraordinary proof. Often times they actively support the specific contributing component technologies but oppose organizing them under a vision they find embarrassingly incredible. Their attitude regarding the interest of competing nations is nonalarmist and might be summed up as, "Good, it will go nowhere and is cost-imposing on them; we should not repeat their mistake."

On the surface, arguments of the opposition are quite strong. They point to the failure of Earth-based solar power to achieve economic viability and ask how the added cost of lifting such systems to orbit could do anything but add cost. To them the idea that such a system could ever have a viable business case violates common sense. They point to decades of failed initiatives to achieve low-cost launch and to a scale of effort in launch and on-orbit service that, given what we find difficult today, seems utterly ridiculous. They rightly point to the extraordinary upfront costs, which at some point in a program would command a substantial share of national resources. They rightly note that the cost of an initial demonstration system is horrifically disproportionate to its actual benefit. Most convincing of all is their argument regarding opportunity costs—that perhaps such a system is in fact technically feasible, but it would be so costly that scarce resources are better spent elsewhere on projects that are less risky and have a more secure, near-term payoff.

The detractors include a host of highly credible people.[13] But it is also possible they are wrong. We should be very cautious in accepting such technological pessimism because there is a long history of prominent men of expertise getting it wrong when they are betting against the aspirations of mankind, especially when harnessed in competition:

"Heavier-than-air flying machines are impossible."

—Lord Kelvin, President of the Royal Society

"Airplanes are interesting toys of no military value."

—Marshal Ferdinand Foch, Ecole Superieure de Guerre, France

"There is no likelihood man can ever tap the power of the atom."

—Robert Millikan, Nobel Prize in physics, 1923

"The biggest fool thing we have ever done. The [atom] bomb will never go off, and I speak as an expert in explosives."

—ADM William D. Leahy to President Truman

"There is no hope for the fanciful idea of reaching the moon because of the insurmountable barriers of escaping Earth's gravity."

—Dr. Forest R. Moulton, astronomer

"Man will never reach the moon regardless of all future scientific advances."

—Dr. Lee DeForest, "Father of Radio and Grandfather of Television"

And this from Vanevar Bush, our own head of defense research and one of America's most visionary men, testifying to Congress just after World War II (1945):

> There has been a great deal said about a 3,000-mile-high angle rocket. In my opinion such a thing is impossible for many years. The people who have been writing these things that annoy me have been talking about a 3,000-mile-high angle rocket shot from one continent to another, carrying an atomic bomb and so directed as to be a precise weapon which would land exactly on a certain target, such as a city. I say, technically, I don't think anyone in the world knows how to do such a thing, and I feel confident that it will not be done for a very long period of time to come. . . . I think we can leave that out of our thinking. I wish the American public would leave that out of their thinking.

Despite this opinion, the United States began work in 1946, and its first ICBM, the Atlas D, became operational in January 1959. Even those closest to the technology can get it spectacularly wrong. Said Wilbur Wright, "I confess that in 1901, I said to my brother Orville that man would not fly for 50 years. Two years later we ourselves made flights. This demonstration of my impotence as a prophet gave me such a shock that ever since I have distrusted myself and avoided all predictions." Orville fared no better, declaring "No flying machine will ever fly from New York to Paris . . . [because] no known motor can run at the requisite speed for four days without stopping."

The problem with experts is they know, only too well, too much about what cannot be done and the difficulties involved. They misperceive as costs and liabilities what are actually investments that could pay back for generations.

We as Airmen should recognize how often the vision and tools we rely upon today have been systematically opposed by technological pessimism of even our own best and brightest and consider carefully the counsel of two men of vision: Arthur C. Clark stated what he called "Clarke's First Law: When a distinguished but elderly scientist states that something is possible, he is almost certainly right. But when he states that something is impossible, he is very probably wrong." Gen Bernard Schriever observed, "The world has an ample supply of people who can always come up with a dozen good reasons why a new idea will not work and should not be tried, but the people who produce progress are a breed apart. They have the imagination, the courage, and the persistence to find solutions."

It is difficult to say what is impossible or ridiculous or to accurately predict the time lines of technological and societal advances. The retort to the technological pessimist's argument that "extraordinary claims require extraordinary proof" is that the extraordinary benefits deserve extraordinary diligence and effort. Nearly every assessment has concluded SBSP is technically achievable.[14] Few argue that SBSP is technically impossible, only that it is economically difficult. But a system, which could actually scale to solve serious problems on the global agenda—sustainable development, climate change, energy security—and simultaneously advance mankind's ability to access and make use of the resources of space deserves serious consideration.

Indeed, one of SBSP's current detractors, Brig Gen Simon P. Worden, articulated the extraordinary benefit as the key to space development: "Power beaming technology is slowly maturing and appears today to involve coherent microwaves or lasers as the mechanisms for carrying the energy. When this technology matures, it should open an era in which the global power grid resides in space and can receive its energy inputs from space-based sources such as large solar-power satellites. Thus, the development of a global energy utility, probably decades into the future, is the key to space development."[15]

But a due-diligence effort would require resources, and Airmen are right to ask whether beyond the abstract argument against "impossible" there is reason to anticipate possible success. What do technological optimists see that makes them evaluate things differently than technological pessimists?

First, SBSP advocates see a system that can deliver constant power at predictable levels as fundamentally different than terrestrial solar power. They believe a first-generation system need not compete directly against coal or nuclear power in price but could service niche markets. Niche markets do exist, including DoD forward locations paying exorbitant prices for electricity, up to tens of dollars per kilowatt-hour (kWh). As early as 2008, the Greater Houston Partnership, an NGO which represents the international oil companies, approached the DoD executive agent for space with a formal letter requesting cooperation in examining the use of SBSP to power remote locations to extract shale gas or even manufacture liquid natural gas (LNG) directly. Proof of the concept in niche markets establishes the public viability and acceptability of the concept, increasing private capital available for financing at a greater scale and catalyzing development of further intellectual capital to lower costs.

Even then, an SBSP system need not be as cheap as nuclear or coal. There are numerous markets around the world that pay nearly an order of magnitude more for power than the lowest US utility rates. Power is also bought at premium prices at peak loads when individual generators must be brought online to cope with additional demand. Because of its unique ability to reach multiple distant markets, a single SPS could sell peak power to multiple urban centers at different times of the day.

The *IAA Report* evaluates a range of potential systems concepts and their inherent technological risks, asserting that new concepts in satellite design involving highly modular systems appear to be the lowest risk. The story of their economic viability as told by the IAA study involves an argument of scale, favoring massively modular systems and reusable launch systems that leverage known industrial learning curves.

Unlike other forms of power generation, SBSP requires no fuel to produce power and comparatively little fuel to maintain its station in GEO. While it would suffer degradation and damage due to particle radiation and micrometeoroid impacts—as would any satellite—it is a massively redundant system of mostly solid-state devices with few moving parts operating in the relatively pristine environment of space. As such it is not expected to require the sort of maintenance a ground-based power plant (subject to weather damage) would require. A nation with the capability to launch 500 times to construct an SPS certainly would have the access and capability to service it.

Therefore, the life cycle cost of a solar-power satellite is dominated by the capital cost of acquisition, measured in dollars per installed watt. This cost is principally driven by two factors: cost of the space hardware (measured in dollars per installed watt) and cost of installation, which is a product of the launched satellite mass (kilograms per watt) and cost of launch (measured in dollars per kilogram).

Space hardware for an SPS is no more complex than consumer electronics. It is expensive today because of extremely low-volume production and high overhead costs. Once a market is established, there is every reason to believe that standard industrial learning curves will apply, as suggested by figure 2.

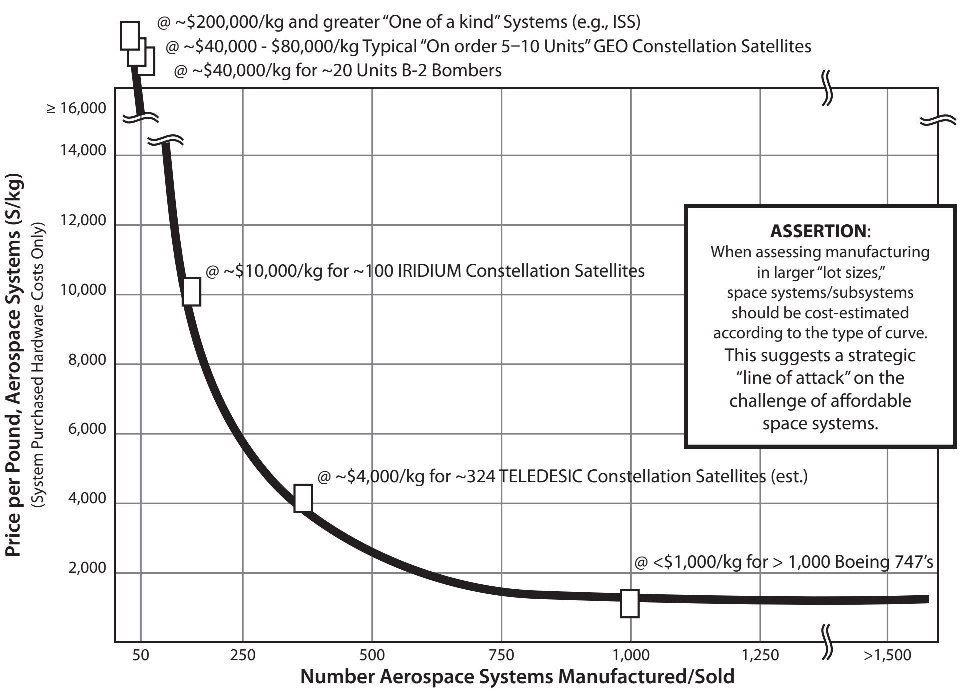

Figure 2. Industrial learning curve applied to aerospace systems (Adapted from John Mankins, "Space Solar Power—Status & Progress," November 2011 presentation to Joint Space Team.)

The same applies to launch. The high cost of space launch is not fuel or even structure, but, again, primarily a result of low-volume production and high overhead costs. The secondary reason for the high cost of launch is reliance on expendable rather than reusable structures and low flight rate. Fully reusable launch vehicles (RLV) have been technically possible for decades, but the upfront cost to develop them was not justified by the market.

SBSP, which would require on the order of 480 to 800 launches per satellite, is a sufficiently large market to justify the upfront investment in an RLV with the expectation of industrial learning curves to apply, bringing the cost of launch into the range where SPSs could be cost-competitive, at least in higher markets. Advocates also note the extraordinary upfront costs that worry the pessimists need not be applied all at once or even using mostly public funding.

The key question before any nation is the commitment to a subscale prototype. The International Space Station cost approximately $100 billion. The IAA estimates that a meaningful demonstration (a subscale system capable of delivering multiple megawatts from GEO) of approximately the mass of the ISS could be accomplished at significantly less cost—the NSSO study estimated $10 billion—and this cost could be spread internationally.

Advocates note that while the benefit of power delivered from this prototype might be small, it would establish the viability of the concept and the believability of terrestrial markets, allowing private capital to be raised. They also believe the program provides other near-term payoffs, simultaneously advancing goals we would pay for anyway: proximity operations, on-orbit servicing, on-orbit construction, in-space maneuver, improved launch, heat rejection, higher specific-power solar cells, and others.

Scale and pace are notoriously easy to underestimate, especially when low initial penetration allows a rapid exponential expansion. Following the Lewis and Clark expedition, Thomas Jefferson, a man of science and vision, declared that it would take at least 100 generations to settle the vast expanse of the West. Instead, Americans hungry for the prosperity it promised populated it within five generations.

The curve for expansion in energy has been even more dramatic. Between 1810 and 1910, oil production increased 100-fold, coal production 300-fold, and gas production 800-fold.[16] Figure 3 provides one scenario for SBSP growth.

When Edwin L. Drake tried to enlist workers to drill for oil in 1859, he was met with, "Drill for oil? You mean drill into the ground to try and find oil? You're crazy." Today it is as difficult to enlist seasoned technical US space engineers to think about "drilling up" as it was for people in 1859 to contemplate how a system of drilling for oil to feed internal combustion engines could economically replace horses with cars, pave an entire continent with concrete and gas stations, and reshape global politics.

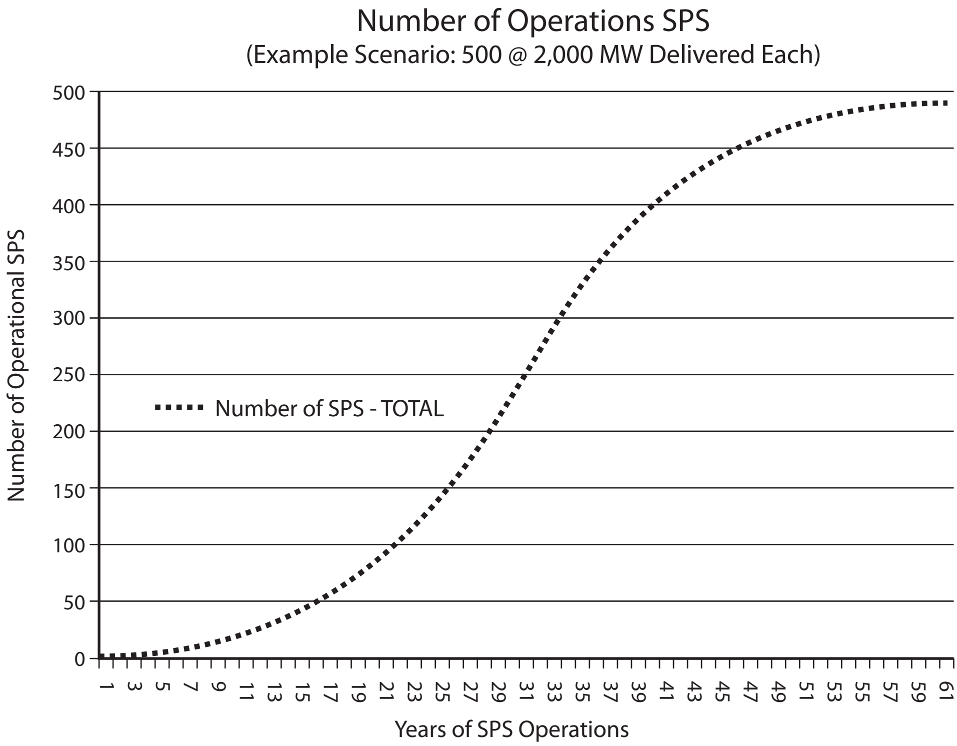

Figure 3. Potential growth scenario to first terawatt (*IAA Report*, fig. 5-2)

International Activity

Those who say it can't be done are usually interrupted by others doing it.

—Joel A. Barker, USAF strategic planning consultant

It may not be prudent to commit large amounts of resources to an unproven idea, but we should also be cautious to self-exempt from strategic competition. It is therefore important to be cognizant of what is happening abroad. While the above-mentioned 2007 NSSO report was for the most part ignored at home, it was understandably read with great interest abroad and appears to have been a catalyst for activity in Europe, Japan, India, Russia, and now China.

By June 2009, Japan announced SBSP as one of nine major national space goals and one of three strategic R&D goals in its *Basic Plan for Space Policy*.[17] It states, "Space solar power may solve the worldwide environmental and energy issues confronting humankind," and articulates that "research and development of the technology necessary to realize the solar power generation system in space for clean and stable energy utilization without any geopolitical influences." In other words, let's make our own energy instead of depending on regions of dubious stability. A nation that has spent a decade, trillions of dollars, and thousands of lives of its Soldiers, Sailors, Airmen, and Marines in conflicts abroad to protect its existing fossil-fuel-based energy ought to realize the sensibility of that.

Japan's space basic plan assigned R&D work to various agencies concerned with space technology, science, and industry as well as universities;[18] stated it would promote commercial use; and stated its intention to use its Kibo module on the ISS as an experimental platform. In November 2009, the Japanese government publically announced a major public-private partnership between METI, MEXT, JAXA, and major industrial giants including IHI, Mitsubishi, NEC, Fujitsu, and Sharp. Press coverage stated there were some 130 engineers studying the concept under JAXA's oversight and examining at least two major designs—one laser, one microwave—and plans for a 10-MW demonstration project by 2020 and a 250-MW prototype.[19] One story even stated that the consortium of 16 companies planned to spend two trillion yen ($21 billion) for a first stage in 2015 and ultimately to have a working 1-GW prototype capable of supplying power to 750,000 homes by 2030.[20]

In December 2009, Russia also expressed interest, with scientists from the Lavochkin Scientific and Production Association Federal State Unitary Enterprise claiming a new design principle and stating that "in order to address the issues of a future energy crisis and to keep up with the developed countries, Russia must begin the research today."[21]

In January 2010, Europe's EADS Astrium announced plans for a demo project, stating it planned to orbit a subscale SPS capable of beaming 10–20 kW of power and would be ready for launch in five years.[22] Matthew Perren, head of innovation at Astrium's headquarters in Paris, stated, "Looking to the future we envisage large power stations in space that are capable of transmitting energy to any point on the planet on demand."[23]

In late 2010, the China Academy of Space Technology (CAST) quietly articulated its interest and program in the *Online Journal of Space Communications*, stating that "the acquisition of space solar power will require development of fundamental new aerospace technologies, such as revolutionary launch approaches, ultra-thin solar arrays, on-orbit manufacture/assembly/integration (MAI), precise attitude control, in-situ resource utilization (ISRU) for deep space exploration and space colonial expansion." It is clear the CAST proponents see SBSP in strategic terms:

> Since SPS development will be a huge project, it will be considered the equivalent of an Apollo program for energy. In the last century, America's leading position in science and technology worldwide was inextricably linked with technological advances associated with implementation of the Apollo program. Likewise, as China's current achievements in aerospace technology are built upon with its successive generations of satellite projects in space, China will use its capabilities in space science to assure sustainable development of energy from space . . . it is necessary for China to launch an SPS-type Apollo project to increase research and development investment in all corollary fields. This will relate to the country's goal of attaining the leading position in both energy and space technology" and that therefore, "the [Chinese] state has decided that power coming from outside of the earth, such as solar power and development of . . . space energy resources . . . is to be China's future direction.[24]

CAST laid out a detailed five-step plan for achieving the first commercial SPS: "In 2010, CAST will finish the concept design; in 2020, we will finish the industrial level testing of in-orbit construction and wireless transmissions. In 2025, we will complete the first 100 kW SPS demonstration at LEO; and in 2035, the 100 mW SPS will have electric generating capacity. Finally in 2050, the first commercial level SPS system will be in operation at GEO."[25]

The concept design was finished in 2010, and in September 2011 came the first highly public announcement where Prof. Wang Xiji, a key drafter of the proposal, stated, "China has acquired sufficient technology and had enough money to carry out the most ambitious space project in history. Once completed, the solar station, with a capacity of 100 MW, would span at least one square kilometre, dwarfing the International Space Station and becoming the biggest man-made object in space."[26]

Professor Xiji articulated, "The area of space and aviation is an emerging strategic industry, and the development of a space solar-energy station requires high-end technology. . . . Such a station will trigger a technical revolution in the fields of new energy, new material, solar power and electricity, and [ultimately] lead to the emergence of several industries . . . and possibly even an industrial revolution." He emphasized that "Whoever takes the lead in the development and utilization of clean and renewable energy and the space and aviation industry will be the world leader." Professor Xiji, one of the acknowledged fathers of the Chinese space program, warned that if it "did not act quickly, China would let other countries, in particular the US and Japan, take the lead and occupy strategically important locations in space."[27]

Clearly our competitors do not seem to share the same technological pessimism that bedevils attempts to begin a US program. As chronicled by author Thomas Friedman, such ambition and technological optimism used to be a part of the ethos and identity of America.[28] One might hope that given China's demonstrated ability to construct mega projects—the massive Three Gorges Dam, high-speed rail, and entire cities, seemingly overnight—that Chinese interest in SBSP might be a wake-up call to what is truly the space race of our generation.

But so far at least, the reaction seems more consistent with the worry expressed by Friedman that the United States, as compared to China, had lost its "can-do" spirit in the early twenty-first century.[29] Airmen, as stewards of America's aerospace power, should not be so complacent. Understanding the critical link between dual-use infrastructure that contributes to access and on-orbit capabilities, an Air Force strategist might then take a much less complacent view of international competition.

> *There are no battles in this strategy; each side is merely trying to outdo in performance the equipment of the other. . . . Its tactics are industrial, technical, and financial. . . . A silent and apparently peaceful war is therefore in progress, but it could well be a war which of itself could be decisive.*
>
> —General d'Armee Andre Beaufre

For years the Air Force has kept the United States out of a major war and kept the world from another global conflict by maintaining technological preeminence and overmatch, practicing what a Cold War textbook called a "Strategy of Technology":

> The Technological War is the decisive struggle in the Protracted Conflict. Victory in the Technological War gives supremacy in all other phases of the conflict. . . . The Technological War creates the resources to be employed in all other parts of the Protracted Conflict. It governs the range of strategies that can be adapted in

> actual or hot war. . . . Military superiority or even supremacy is not permanent, and never ends the conflict unless it is used. The United States considers the Technological War as an infinite game: one which is not played out to a decisive victory. We are committed to a grand strategy of defense, and will never employ a decisive advantage to end the conflict by destroying our enemies. Consequently, we must maintain not only military superiority but [also] technological supremacy. The race is an alternative to destructive war, not the cause of military conflict. . . . The United States is dedicated to a strategy of stability. We are a stabilizing rather than a disturbing power, and our goal is preserving the status quo and the balance of power rather than seeking conquest and the final solution to the problems of international conflict through occupation or extermination of all opponents. In a word, the U.S. sees the Technological War as an infinite game, one played for the sake of continuing to play, rather than for the sake of "victory" in the narrow sense.[30]

That is not to imply that Airmen should recommend a zero-sum orientation toward SBSP competition, only that America should get its head in this game.

Because it is the policy of the United States to pursue international cooperation in space and take the lead in multilateral efforts which enhance stability and transparency in space, Airmen must consider not only the threat of losing an important technical competition but also the opportunity international cooperation could provide to advance US interests through partnerships in the domains under their stewardship.

Aerospace competition is not only technical; it also has an aspirational moral dimension, as nations are measured, admired, and respected not only by their accomplishments but also by their ambitions. Former USAF strategist Col John Boyd made clear the strategic value of vision: "What is needed is a vision rooted in human nature so noble, so attractive that it not only attracts the uncommitted and magnifies the spirit and strength of its adherents, but also undermines the dedication and determination of any competitors and adversaries."[31]

SBSP opens the doors to engagement with nontraditional partners and could promote exactly the kind of international collaboration called for in our *National Space Policy*. At least one nontraditional partner has already opened the door. In 2007 at Boston University, then-president of India, Dr. A. P. J. Kalam, laid out a 50-year vision for space with SBSP at the core.[32] Dr. Kalam has continued to articulate his vision since, even lending his name to a (so far ignored) proposal for Indo-US cooperation with the largest citizen space advocacy group, the National Space Society (NSS).[33]

In joint statement after joint statement, both countries reiterate their desire to cooperate in space, in clean energy, in climate change mitigation and sustainability, in strategic and high technologies. Both sides hand wring that after the "123" civil-nuclear deal, there is no "big idea" animating the strategic partnership. SBSP seems an obvious choice that would and has been floated by several important think tanks in both India and the United States.[34] The recent CFR-Aspen report, *The United States and India: A Shared Strategic Future*, stated, "On climate change and energy technology, the collaboration should: Conduct a joint feasibility study on a cooperative program to develop space-based solar power with a goal of fielding a commercially viable capability within two decades."[35]

The Opportunity and Recommendations

> *[It was the] consensus of the IAA that significant progress could be accomplished during the next 10–15 years—leading to a large but sub-scale SPS pilot plant.*
>
> —*IAA Report*, 2011

The *IAA Report* insists that within 15 years, the first meaningful prototype, approximately the mass of the International Space Station, could be in orbit, producing megawatts of power and delivering it in the range of $1–5 per kWh.

While the production scenario for four or more operational satellites favors a new reusable launch vehicle, the IAA study suggests (see fig. 4) that a moderate-sized demo could be emplaced least expensively with existing launch vehicles at less than the cost of the ISS. For those looking for aerospace jobs, those desiring a Manhattan Project of energy, and those seeing energy as the space race and Apollo project of our generation, that is quite a "shovel-ready" project.

Unlike other potential civil space program goals—such as human travel to the moon, Mars, or an asteroid, which only obliquely contribute to national security space—a national SBSP program would more directly benefit the DoD. The construction of a large demo necessarily advances on-orbit competencies in proximity operations, construction, servicing, and maintenance and includes the development of a space tug, which enhances on-orbit maneuver, and a large block buy of expendable commercial launch vehicles that would lower the cost for national security payloads. If successful, a proven delivered cost of $1–5 per kWh for power in the megawatts for a first-generation system is significantly less than the cost of electricity US forces are paying today after fuel is convoyed or helicoptered to forward locations and would establish the market for RLVs, further lowering the cost for DoD payloads in the longer term and opening the potential for more regular access to space.

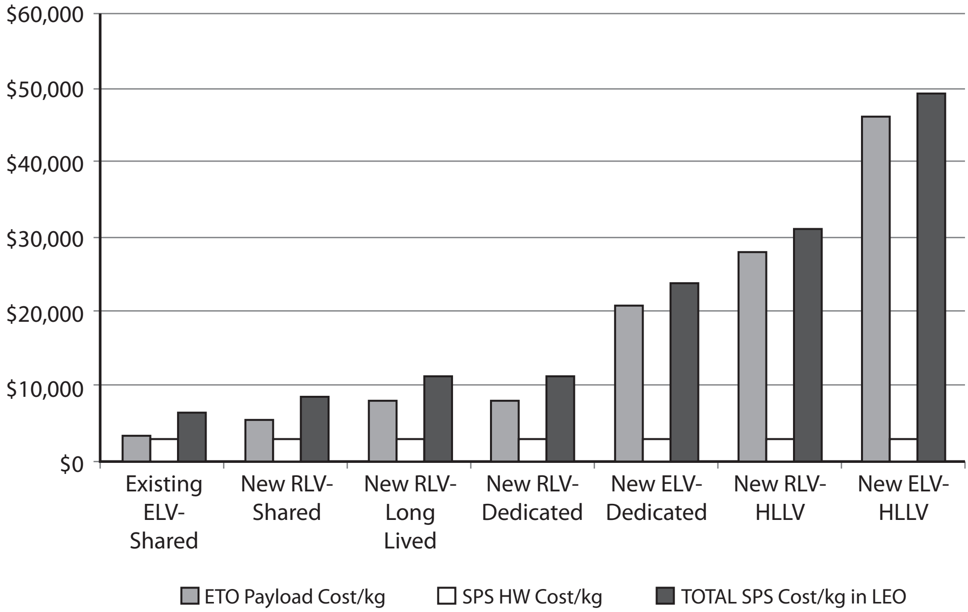

Figure 4. Launch options for a moderate-scale SPS pilot plant @400 mt (*IAA Report,* fig. 7-7)

The United States already participates in an international project of comparable duration, cost, and technological risk, the International Thermonuclear [Fusion] Experimental Reactor (ITER)[36] being constructed in the south of France,[37] but even if successful in achieving break-even energy, it will not provide the above benefits to the nation.

The longer-term benefits for our industrial base are even more profound. Total revenues in the space sector today are only $275 billion—mostly from satellite TV[38]—but revenues in the energy world exceed $7 trillion annually. The market for green power is enormous. The IAA estimates the demand for energy from renewable sources will need to grow from roughly 12,000 billion kWh per year in 2010, to more than 110,000 billion kWh per year in 2030–2040, and to more than 430,000 billion kWh per year by 2100—a 36-fold expansion. Over the next 20 years, the world is going to invest over $12.4 trillion in new infrastructure within the power sector (China, $3.1 trillion; the United States, $2.1 trillion;[39] India, $2.3 trillion;[40] Russia, $1.9 trillion;[41] and Europe and the UK, $3 trillion[42])!

That market translates directly into jobs both at home and abroad. Consider that a $1 billion investment in utility-scale photovoltaic (ground) solar would result in nearly 10,000 direct and 19,000 total jobs (well-paying jobs) in the United States and nearly 5,000 direct and 19,000 total new jobs in China, purely for 400 MW of additional capacity, according to a 2010 industry-paid study by Garten-Rothkopf. That 400-MW total is small compared to what is contemplated in SBSP, where both China and Japan talk of 1-GW individual plants.

If a mere $1 billion for terrestrial photovoltaic would result in 19,000 new jobs at home, consider that the $10 billion demo proposed in the NSSO report might be expected to generate 190,000 total jobs. There is the potential for significantly more if, as Professor Xiji notes, it would create whole new industries and spark an industrial revolution. The demo is just the beginning.

Based on the data in figure 5, the IAA estimates that should SBSP achieve financial viability and full output, "annual employment on the order of 5,000,000 individuals might be realized eventually."

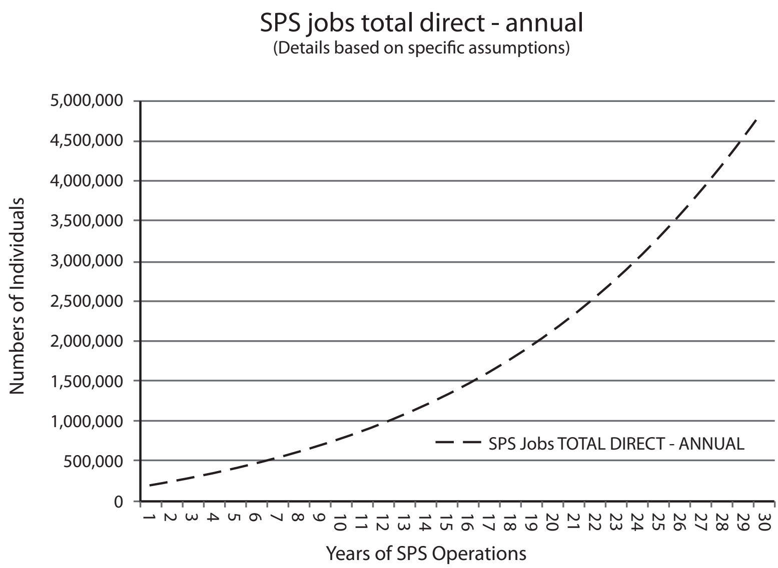

Figure 5. IAA job growth scenario to 1,000 GW of power[43] (*IAA Report* fig. 5-6, assuming logistics curve growth to 500 x 2,000-MW [2-GW] satellites)

Some argue that these austere times are not the right time to begin such a program. But it has always been in times of economic depression or challenge that the United States has begun major energy and infrastructure projects. It was in the context of conflict, hot and cold, that the United States began the Manhattan and Apollo projects. It was during the Great Depression when the United States launched such initiatives as the Tennessee Valley Authority rural electrification program. SBSP combines space, energy, infrastructure, innovation, and frontier spirit and plays to American strengths. Vision attracts talent and capital. It is when America is down that it reinvents itself with a still larger, frontier-expanding vision. If not now, when will we step out into the next great Manhattan-like project, and how will we continue to be the world leader in technology and innovation?

Right now there is no organization with a mandate to do SBSP. NASA's internal constituencies are for manned and robotic exploration. It sees a massive industrial energy project as the reason we have a Department of Energy (DOE). The DOE says it supports the vision of infinite green energy, but that the essential technology problems involve space technology, and that is why we have a national space agency. The DoD has interests in all supporting technologies—space access, in-space maneuver, on-orbit construction, beamed energy—but it is neither America's department of energy nor its civil space agency and already is underfunded to meet the core requirements of its chief customer, the war fighter.

If America is going to compete in this vital, exciting endeavor, it will have to organize for success, giving some official entity the mandate and providing the necessary resources. That will not happen without advocacy from the stewards of US technical preeminence in aerospace—Airmen.

We, as Airmen, who have the historical identity as the "technology force," who understand the critical importance of our national technology base in securing national and international security through technological preeminence, and who are the stewards of the domain of space, must rise to the occasion—lending our voices to the urgency of the hour and supplying the vision for the advancement of human activity and commerce in this new domain—and advocate for a national program to realize the promise of a new age of "space power." SSQ

Notes

1. Advance presentation of the *IAA Report* to the Joint Space Team, Pentagon, November 2011.

2 . International Association of Astronautics (IAA), *Space Solar Power, the First International Assessment of Space Solar Power: Opportunities, Issues and Potential Pathways Forward* (Paris: IAA, 2011). [Elsewhere: the *IAA Report*]

3. "Launch History," *Satellite on the Net*, http://www.satelliteonthenet.co.uk/index.php/launch-history.

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5. James M. Snead, 2009 International Space Development Conference presentation. According to Snead, geosynchronous orbit could, in theory, hold as many as 66,200 5-GW SPSs at 100-percent slot use, supplying as much as 330 TW of power against a 2100 projected requirement of only 55 TW to supply all of humanity's energy needs.

6. *National Space Policy of the United States of America* (Washington: The White House, June 2010), http://www.whitehouse.gov/sites/default/files/national_space_policy_6-28-10.pdf.

7. National Security Space Office (NSSO), *Space-Based Solar Power as an Opportunity for Strategic Security* (Washington: NSSO, 2007), http://www.nss.org/settlement/ssp/library/nsso.htm.

8. For an excellent discussion, see Brent Ziarnick, "To Command the Stars: The Rise of Foundational Space Power Theory," http://www.schriever.af.mil/shared/media/document/AFD-070906-081.pdf.

9. NASA, Office of the Chief Technologist, "2011 NAIC Phase I Selections," http://www.nasa.gov/offices/oct/early_stage_innovation/niac/2011_phase1_selections.html.

10. In fact, from 2007 to 2008 the AFRL had a small exploratory project—just enough to hold two small workshops. During the changeover of administrations, it was directed to cancel further activity as there was worry that "someone in the new administration [with its green energy agenda] would like it, and the AF would be stuck with a bill."

11. Personal e-mail to the author, 8 November 2011.

12. Personal e-mail to the author, 5 October 2011.

13. Skeptics and critics of the viability of the concept have included at least one past chief scientist of the AF, researchers in AFRL's power and propulsion directorate (AFRL/RZ) and its office of scientific research (AFOSR), a NASA center director, a former national security space architect, and past members of the executive office of the President's Office of Science and Technology Policy (OSTP).

14. DOE and NASA studies (1977–81); National Research Council, "Laying the Foundation for Space Solar Power" (2001); NSSO, "Space-Based Solar Power as an Opportunity for Strategic Security"; and IAA, *The First International Assessment of Space Solar Power: Opportunities, Issues and Potential Pathways Forward* (2011). All of these sources can be found at http://www.nss.org/settlement/ssp/library/index.htm.

15. Simon B. Worden and John E. Shaw, *Wither Space Power? Forging a Strategy for the New Century* (Maxwell AFB, AL: Air University Press, 2002), 81, http://www.au.af.mil/au/awc/awcgate/au/wordenshaw.pdf .

16. Vaclav Smil, *Energy in World History* (Boulder, CO: Westview Press, 1994), 185.

17. Strategic Headquarters for Space Policy, *Basic Plan for Space Policy*, 2 June 2009, available in English at www.kantei.go.jp/jp/singi/utyuu/basic_plan.pdf.

18. These included the Japan Aerospace Exploration Agency (JAXA), Ministry of Economy Trade and Industry (METI), Ministry of Education, Culture, Sports and Technology (MEXT), and Institute for Unmanned Space Experiment Free Flyer (USEF).

19. Karyn Poupee, "Japan Eyes Solar Station in Space as New Energy Source," *Physorg.com*, 8 November 2009, http://www.physorg.com/news176879161.html.

20. Alex Salkever, "Japan Plans Massive Solar Power Station to Orbit Earth," *Daily Finance*, 3 September 2009, http://www.dailyfinance.com/2009/09/03/japan-plans-massive-solar-power-station-to-orbit-earth/.

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22. See Jonathon Amos, "EADS Astrium develops space power concept," *BBC News*, 19 January 2010, http://news.bbc.co.uk/2/hi/8467472.stm; Lin Edwards, "European Company Wants Solar Power Plant in Space," *Physorg.com*, 21 January 2010, news183278937.html; Richard Gray, "Lasers to Beam Energy to Earth from Space," *Telegraph* (London), 23 January 2010, http://www.telegraph.co.uk/earth/energy/solarpower/7060015/Lasers-to-beam-energy-to-Earth-from-space.html; and "Lasers to Beam Solar Energy from Space to Earth," *Times of India*, http://timesofindia.indiatimes.com/home/science/Lasers-to-beam-solar-energy-from-space-to-earth/articleshow/5496009.cms.

23. "Lasers to Beam Solar Energy from Space to Earth."

24. Gao Ji, Hou Zinbin, and Wang Li, "Solar Power Satellites Research in China," *Online Journal of Space Communication* 16 (Winter 2010), http://spacejournal.ohio.edu/issue16/ji.html.

25. Ibid.

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27. Ibid.

28. Thomas Friedman, "That Used to Be Us: How America Fell Behind in the World It Invented and How We Can Come Back," *New York Times*, http://www.thomaslfriedman.com/bookshelf/that-used-to-be-us.

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31. Boyd's lectures can be found at http://www.ausairpower.net/APA-Boyd-Papers.html.

32. Dr. A. P. J. Abdul Kalam, "The Future of Space Exploration," video of speech, http://www.bu.edu/pardee/space-abdul-kalam/.

33. See various articles and videos by Dr. Kalam at http://www.nss.org/news/releases/pc20101104.html.

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43. *IAA Report*, fig. 5-6, assuming logistics curve growth to 500 x 2,000 MW (2 GW) satellites.

Author's Correction

The Air Force Energy Horizons report was in draft form when this article was written. The final document does mention space-based solar power. The reader can find the entire report using the link below, and the space-based solar power excerpt is shown here. The author regrets this omission.

AF Energy Horizons United States Air Force Energy S&T Vision 2011–2026, AF/ST TR 11-01 31 January 2012 refer p. 27….
http://www.af.mil/shared/media/document/AFD-120209-060.pdf

> On orbit, the utilization of energy is generally relegated to the asset that generates the power. This greatly reduces the potential capability of these systems. However, new technologies may allow for increased capability for these systems through the wireless transfer of power. While there are many challenges in space-to-earth power beaming, space-to-space power beaming could be transformational and is an area which could open up entirely new ways to power sets of–fractionated, distributed satellite systems. Like air refueling, space power could be transformational, and could transfer or beam energy to other space assets, enabling them to be smaller, more survivable, and more capable than current systems. It is foreseeable that wireless energy transfer may dominate the amount of energy utilized on-board satellites, due to the technology constraints of on-orbit energy production and storage. This technology could allow for more capable systems to be launched as more payload would be available for operational systems.