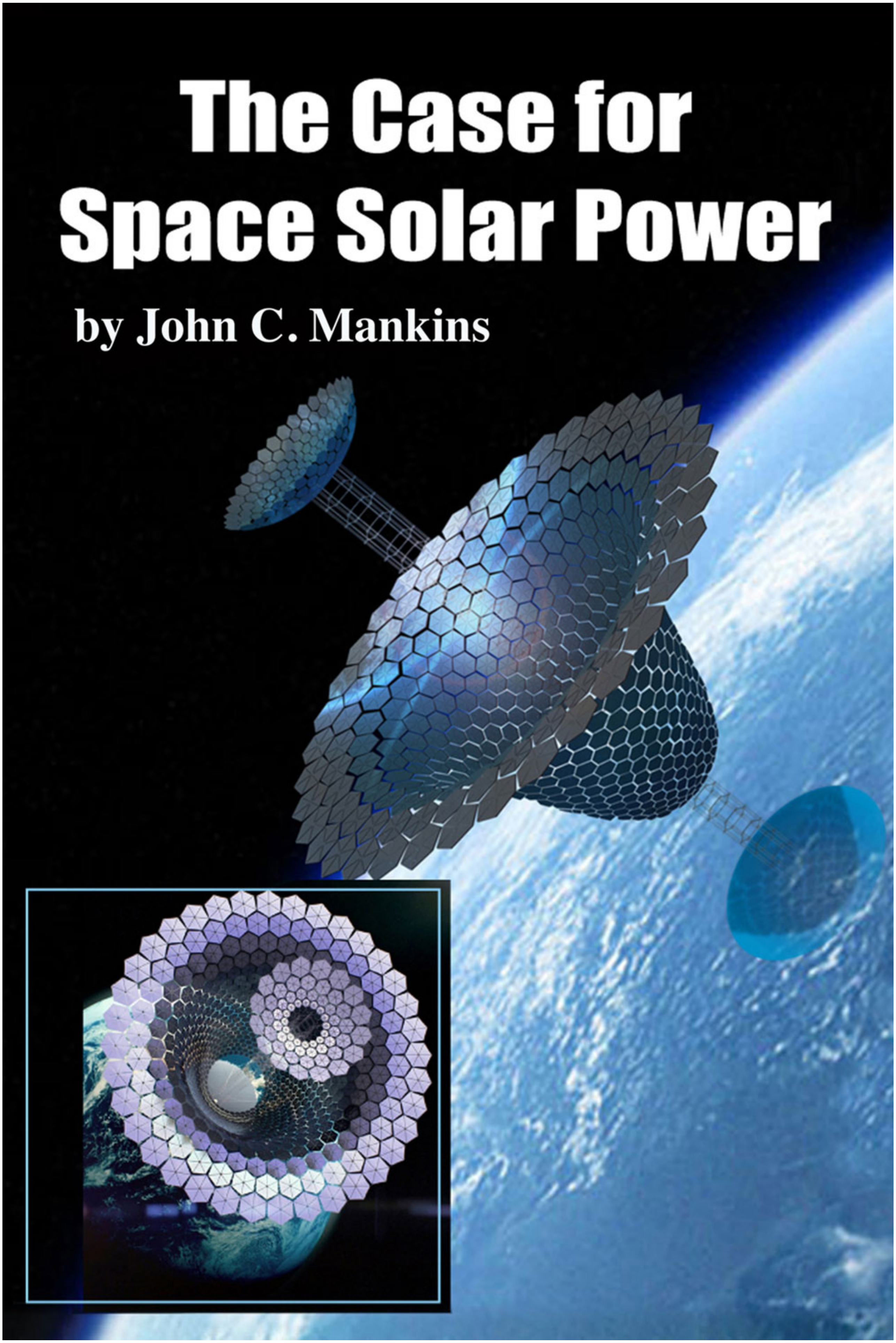
The Case for Space Solar Power

by John C. Mankins



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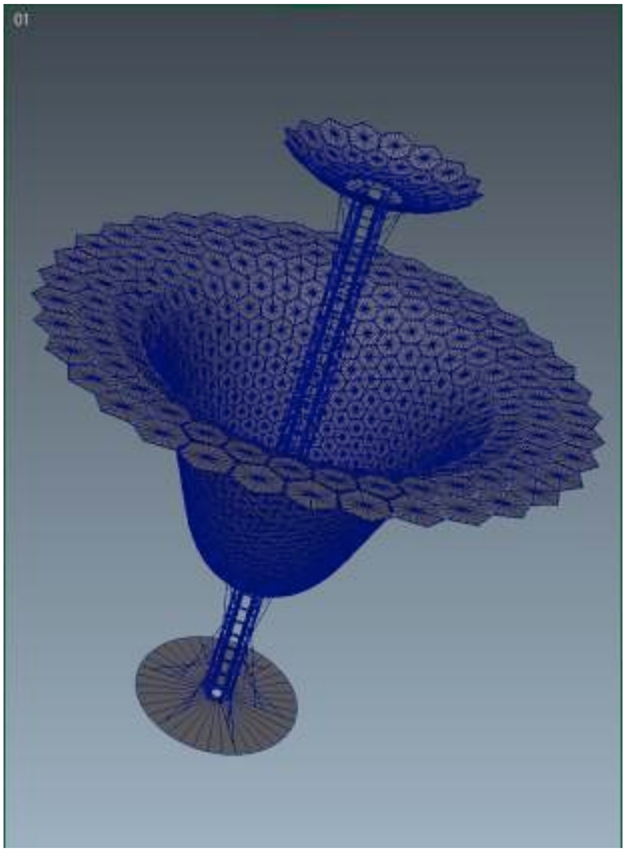

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First and foremost, a debt is owed to: Dr. Peter Glaser, inventor of the Solar Power Satellite (SPS); to William (Bill) Brown, a pioneer in the enabling field of wireless power transmission (without which SPS would be impossible); to Professor Nobuyuki Kaya of Kobe University, long-time leader of wireless power transmission research in Japan and international champion of Space Solar Power (SSP); and to Ivan Bekey, formerly of the Aerospace Corporation and NASA, who introduced me to the SPS concept in 1995.

A debt is owed also to others who paved the way for Space Solar Power through their years – if not decades – of involvement in and support for SSP and SPS research and development. Many of these individuals are mentioned in Chapter 3 (which presents a brief history of SSP), while others are not but probably should have been. (To anyone omitted, apologies in advance for the oversight.)

Finally, the author owes a great debt to those who supported two recent efforts concerning SSP: the 2008-2011 International Academy of Astronautics (IAA) "First International Assessment of Space Solar Power," and the 2011-2012 NASA Innovative Advanced Concepts (NIAC) program Phase 1 project, "SPS-ALPHA (Solar Power Satellite via Arbitrarily Large Phased Array)." This included a number of individuals, as well as two organizations: the FATE Consortium, and SPACE Canada, both of which provided support when it was critically needed.

(www.nasa.gov/directorates/spacetech/niac/NIAC_funded_studies.html#.UorOIcRJPEk)

Foreword

As its name suggests, this book aspires to make "The Case for Space Solar Power" and to persuade the reader that the time has come to realize this transformational vision. "By pursuing" Space Solar Power, humanity may also open the door to affordable and ambitious exploration and development of our solar system.

This is not to say that there are no hurdles to be overcome or that the technologies and systems needed to achieve commercially viable Space Solar Power are sitting "on the shelf" just waiting to be used. However, the gap between what we actually do in space and what we might do in space – using technologies that are already in use on Earth or exist in the laboratory – has grown so great that ambitious goals such as Space Solar Power may be realized in the reachable future far more readily than most imagine, and at far less cost than past visionary goals of the past, such as putting a man on the Moon in the 1960s.

The text is organized into five major parts, progressing from an introduction to the challenges we face vis-à-vis energy and the environment, to assembling a business case for Space Solar Power. There are a great many figures and tables; this is a topic that seems to lend itself to – if not outright demand – visualization of both the concepts and the data. The book concludes with a forward look at "what's next" for Space Solar Power. At the end of the day, too few people know much about this exciting opportunity – and most have never even heard of it.

I hope this book can begin to change this *status quo* and successfully make the Case for Space Solar Power.

John C. Mankins

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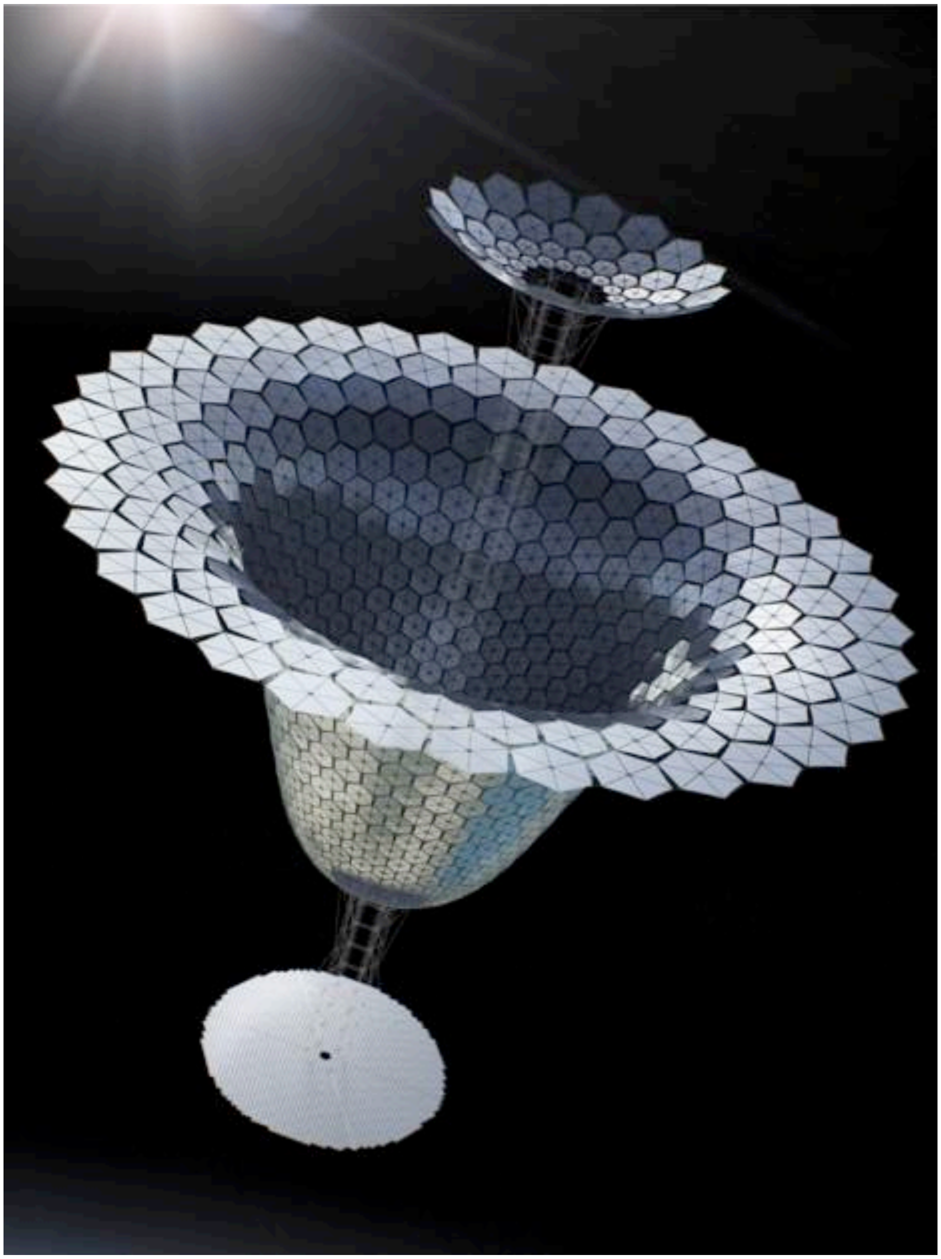
Part 1

Overview



Chapter 1

The Vision of Space Solar Power

"There is not the slightest indication that nuclear energy will ever be obtainable. It would mean that the atom would have to be shattered at will."[1]

Albert Einstein (1934)

The Promise

Reliable and affordable energy is fundamental to our global society. It is only through the availability of vast amounts of cheap energy – largely from fossil fuels – that the world's population grew from less than one billion in 1800 to more than seven billion in 2013. Most of that energy is used in the form of electricity, with most of that electricity generated through the burning of coal. As the world's economy has grown over the past three decades – raising the quality of life in China, India, and many other countries – the need has become all the more urgent to increase the energy available for industry, transportation, for heating and cooling, for personal use, and so on. Just before the beginning of the economic crisis in 2008, this soaring demand resulted in drastic increases in the prices of most conventional sources of energy. In addition, during the past several decades concerns have emerged that society's overwhelming dependence on fossil fuels is driving other kinds of change: growth in atmospheric concentrations of greenhouse gases (such as carbon dioxide and methane) and increases in average global temperatures. If left unchecked, most scientists now believe that increasing concentrations of greenhouse gases in the atmosphere will alter the global climate by the end of this century, with sweeping impacts on societies across the globe.

As a result, there is great interest in finding new, more sustainable alternatives to fossil fuel-based energy supplies. Of the non-fossil fuel alternatives that exist – hydroelectric power, nuclear power, wind power, wave energy and others – one of the most accessible and intuitively attractive is solar power. However, despite significant advances in performance, reductions in cost, and dramatic growth in the total deployed capacity in recent years, ground-based solar power remains largely a niche technology, providing only a small portion of society's energy needs.

Fortunately, there is a promising alternative to conventional ground-based solar power systems, albeit one that is a relatively unknown: **Space Solar Power**.[2]

The energy in the sunlight found in space near Earth is considerably greater than that which remains in sunshine after it passes through the atmosphere, even on a clear day. In fact, the power intensity of sunlight in space is about 1,368 watts per square meter, as compared to only about 1,000 watts/m^2 at noon on a clear day near the equator – a drop of about twenty-seven percent (27%).[3] Figure 1-1 presents the difference between sunlight on Earth and in space, illustrating the hour-by-hour daily solar energy at geostationary Earth orbit (GEO) and comparing it to the average solar energy at a typical location at around 30º north latitude on Earth (in this case, a location such as central Texas in the U.S.) in June and in December.

This initial attenuation of sunlight is compounded by additional factors: the day-night cycle, a reduction averaging roughly sixty percent (60%); changes in the available sunlight due to the weather, a reduction of twenty percent (20%) for light clouds, but up to seventy-to-eighty percent (70%-80%) for heavy clouds; and changes due to the seasons, of up to sixty percent (60%) or more, depending on the latitude of the site. The combination of these factors results in the available solar energy in space at around GEO or above being about ten times greater than the best average available at most locations on Earth.

As shown, on the ground there can be a difference of roughly a factor of three in the solar energy available in summer versus winter. This seasonal variability is a significant deterrent to the use of ground-based solar power for any more than a small fraction of the power used in a given market.

Figure 1-1 Hour-by-Hour Average Difference in Solar Energy
at a middle latitude on North America in June and December, vs. GEO in Space

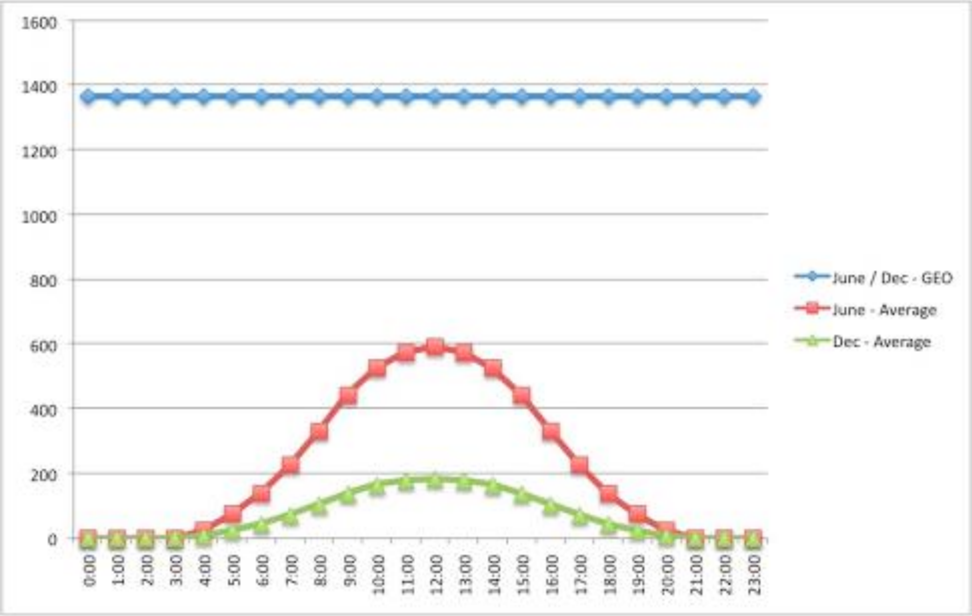
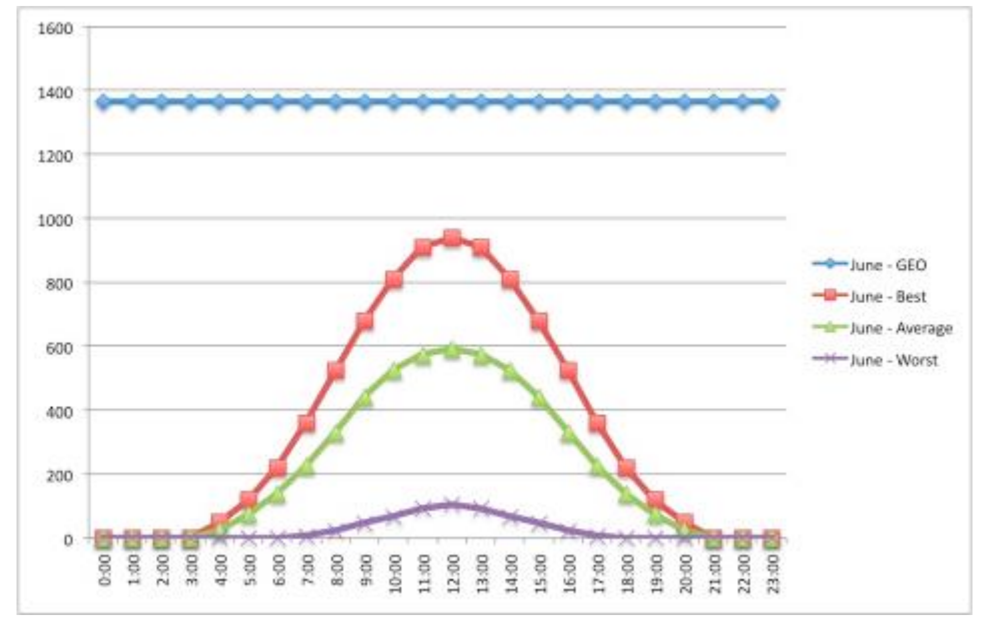


Figure 1-2 focuses on the month of June in the same location, comparing the hour-by-hour solar energy at GEO and on Earth for the best day and for the worst day of the month. Looking at the data, it is clear that the available solar energy at a typical location on Earth on the worst day – even in the best month – is a tiny fraction of the solar energy available in space nearby.

Of course, as the price of photovoltaic (PV) arrays have dropped in the past five years or so (a positive effect of increases in production due to government incentives in the US and Europe, and a resulting massive scale-up in production – in China, for example), even with the limitations of sunlight intensity the levelized cost of electricity (LCOE) from those arrays has become more competitive. Or, at least they are competitive up to a point. As long as PV arrays are used as a small contributor in conjunction with other sources of energy (e.g., less than 15%-20% of the total), power companies can compensate for the highly intermittent nature of ground-based solar power. The challenges for ground-based photovoltaic (PV) arrays become much harder if one attempts to use them to provide the majority of the energy demanded by the market – what is called “baseload” power.

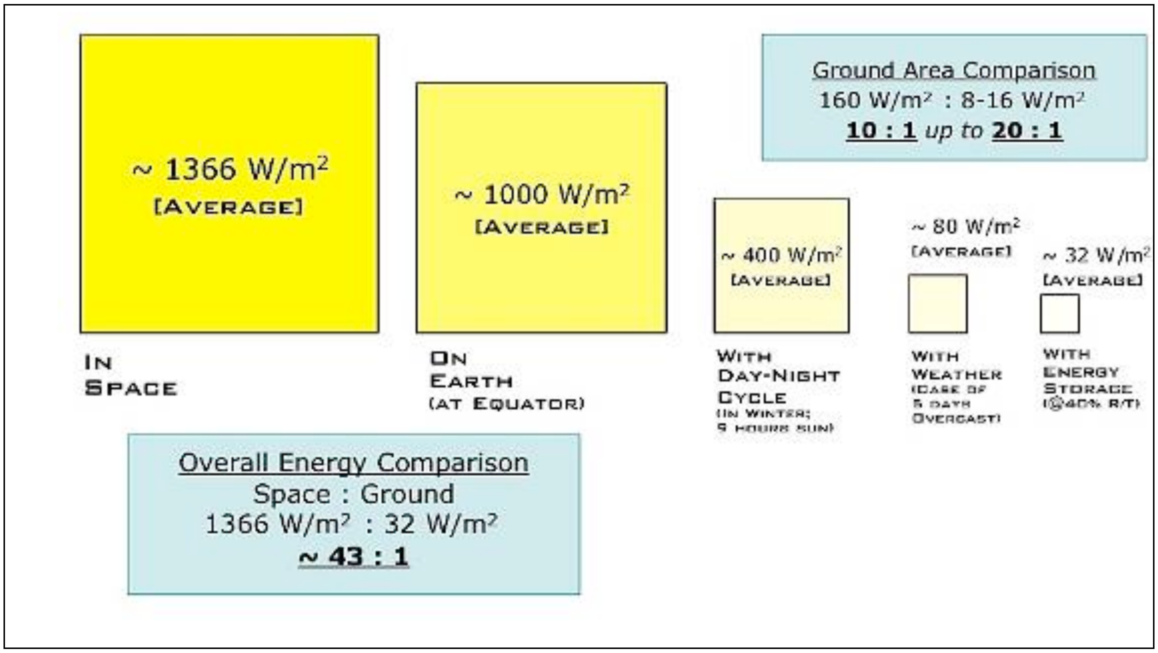
These difficulties arise because primary power plants are expected to provide energy almost continuously – not occasionally. Natural gas turbine, coal-fired, nuclear, and hydroelectric power plants all provide baseload power (i.e., electricity that is available almost 24 hours a day, 7 days a week, in every season and all types of weather).[4] Unfortunately, ground-based solar arrays can only provide baseload power if they are integrated with large-scale energy storage systems (e.g., pumped water storage, flywheels, or batteries). Two additional limitations come into play in considering such large-scale terrestrial solar power systems: inefficiency and weather. Figure 1-3 compares the aggregate of these factors on the effective energy available in space versus on Earth.[5]

Figure 1-2 Hour-by-Hour Average Differences in June Solar Energy in Space at GEO vs. Earth (at the same location as that in Figure 1-1)



First, energy storage systems are not perfect; during the roundtrip of going into a storage system, waiting until needed, and then being drawn back out for use, some of the energy is lost in the form of waste heat. These losses can total as much as 50% of the original energy. Second, overcast weather typically lasts longer than a single day; to provide baseload power, ground solar arrays must be over-sized to deliver enough power during daylight hours not only for immediate use but also to recharge energy storage systems that will in turn deliver baseload electricity over multiple days or even weeks.

Figure 1-3 Comparison of a Solar Array on Earth *vs* Space for Baseload Power



Taken together for local baseload power, the average area required for a solar array on the ground can be more than 40-times larger than area required for a solar array in space. As shown, the required area on the ground to deliver a given amount of energy may be from 10-times to 20-times greater for ground-based solar versus space solar power. For baseload power, the effective energy intensity (i.e., power per square meter of area) varies by as much as 40-to-1 between solar energy in space versus solar energy on the ground.

None of this diminishes the importance of ground solar power in our energy future. However, it does establish the possibility that solar energy from space *might* be an attractive possibility for future sustainable energy; however, this possibility can only become an economic reality if a number of critical technical challenges are overcome.

So, given that harvesting solar energy in space seems like a great idea, why hasn't it already been accomplished? If we tried to implement it, how would Space Solar Power work?

SSP Technological and Engineering Challenges

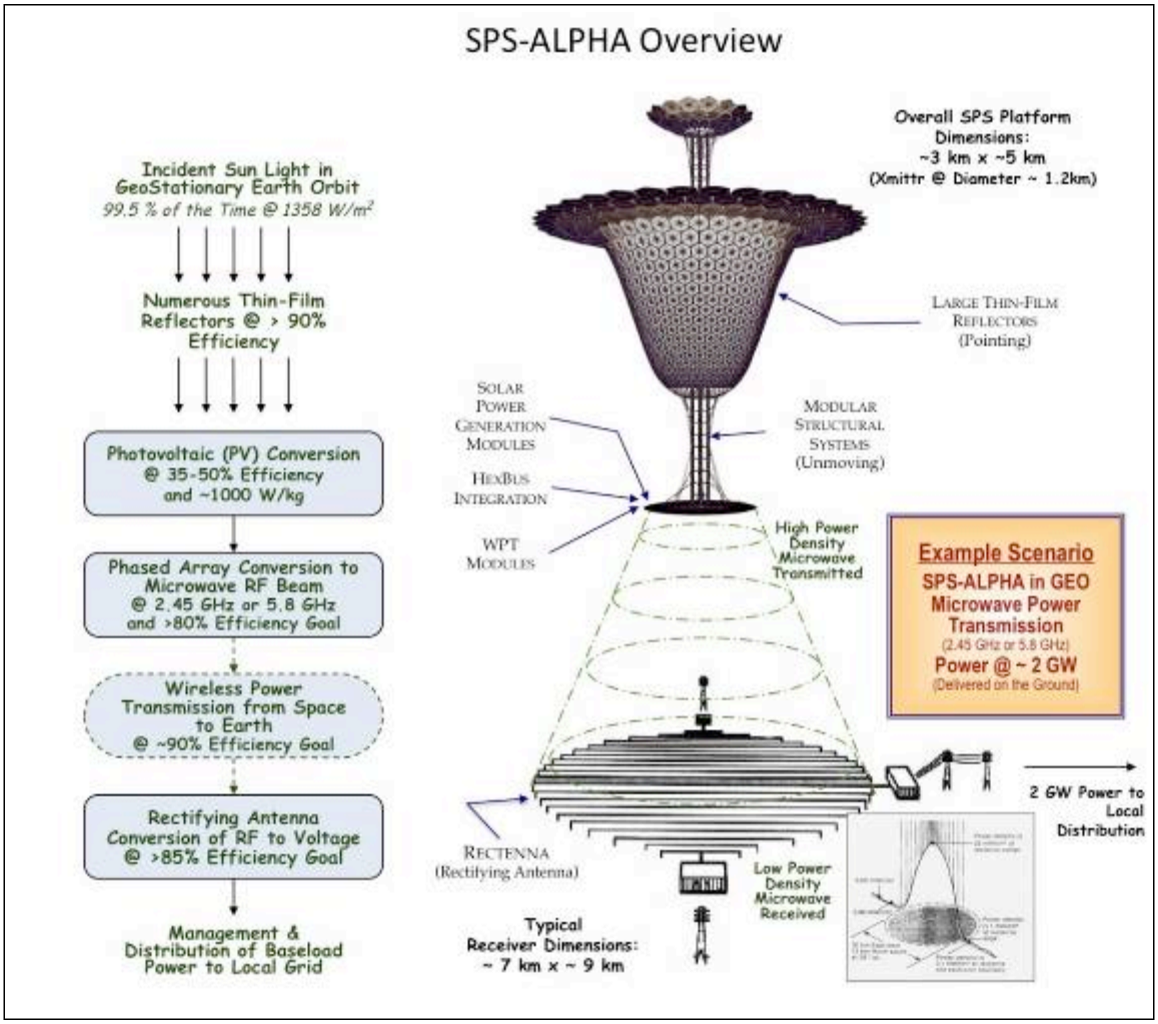
The basic concept is deceptively simple. Sunlight is captured in space at a large platform known as a Solar Power Satellite (SPS), converted into a beam of energy, and efficiently sent to Earth where it is converted once more into voltage and distributed for use.[6] The details are much more challenging.[7] Figure 1-4 illustrates the overall SPS concept.

In the case of one promising new SPS architecture – "SPS-ALPHA" (Solar Power Satellite by means of Arbitrarily Large Phased Array) – sunlight is first intercepted by a large number of individually pointed lightweight thin-film mirrors and redirected to a high-efficiency photovoltaic array and converted into electrical voltage. Spacecraft wiring conveys the resulting electricity to an array of solid-state radio frequency (RF) transmitters that is actively steered, controlling the phase of each of the individual transmitters using a precise reference signal sent from Earth. The phased array then coherently transmits the power at a microwave frequency (such as 2.45 GHz – corresponding to a wavelength of about 5 inches, or 12 centimeters) to a receiving antenna on Earth where it is converted and conveyed just like any other energy source to customers on the ground.

Of course, the SPS platform must first be manufactured and launched into space – and this is a tough challenge. Space solar power platforms are of necessity exceptionally large in order to capture and deliver a meaningful amount of solar energy. As a result, SPS typically involve many, many launches of multiple reusable launch vehicles (RLVs) to place the pieces of the solar platform into a low Earth orbit (LEO) at a very low cost. From there, high-efficiency solar electric propulsion (SEP) "freighters" would be used to transport the building blocks to a much higher "geostationary Earth orbit" (a distance of 22,300 miles or 35,700 km) – from where a satellite can continuously see a range of locations on the ground (Most communications satellites are located in GEO for this reason). Once all of the pieces of the SPS are delivered, they must be assembled into the operational satellite; only then can energy begin to be delivered to the Earth.

There are no "show-stoppers" in the concept of Space Solar Power; no aspects of the physics are unknown. This compares well with other ambitious future energy concepts such as fusion power for which major uncertainties in the basic physics of the power source remain to be resolved. However, there are a number of critical technology challenges that must be overcome in order for space solar power to become economically viable.

Figure 1-4 Example Solar Power Satellite End-to-End Architecture



Credit: Artemis Innovation Management Solutions LLC (2013)

Placing a Solar Power System Affordably in Space

The following are the key challenges that must be resolved in order for SPS to become economically feasible.

Low-Cost Access to Space

It is crucial that the systems used for space transportation must be transformed in order for space solar power to become economically viable. The Expendable Launch Vehicles (ELVs) available today (c. 2013) deliver hardware at costs between $10,000 and $20,000 per pound. Fortunately, most of these systems have the potential to cost much, much less if they are used much more frequently. In addition, the single greatest ELV cost component is the launch hardware, which is only used once. (Imagine the cost of a ticket from Washington to Los Angeles if the $100 million jet aircraft for the flight was only used once!) The long-standing solution to this problem is called a "reusable launch vehicle" (also known as an RLV).8 Such a vehicle has the potential to drastically reduce the cost of access to space—but only if it can be used many, many times.

Also, much more affordable in-space systems are needed to move the pieces of an SPS from LEO to GEO. Such systems need to be both highly fuel efficient and reusable; it will never be possible to operate affordably in deep space if the systems that take us there are discarded with every use. Fortunately, modular, highly reusable, solar electric propulsion systems have been defined and various component technologies developed that could transport the parts of a solar power satellite from low Earth orbit to GEO. Together, reusable launch vehicles and reusable solar electric "tugs" have the potential to transform operations in space in LEO and beyond.

Intelligent Modular Systems

In addition to the range of advances that are needed in space transportation and other areas, it is vitally important that an SPS be both affordable and capable of easy space assembly, maintenance, and servicing. The SPS systems concepts of the 1960s-1980s involved large, piece-part platforms that relied upon large space-based factories for their construction and later maintenance. However, beginning in the mid-1990s (with NASA's "Fresh Look Study" of Space Solar Power[9]), the most promising SPS concepts have relied on a new approach: intelligent modular systems. With this approach, exceptionally large space systems would "self-assemble" from many hundreds to thousands of essentially identical and individually intelligent modular elements – exhibiting behaviors that are comparable to those of a hive of bees or a colony of ants.

Lightweight Systems

Of course, whatever the details of the platform systems, it is critical that SPS hardware be as light as possible. There are a range of novel approaches and component technologies that can reduce the weight of future SPS platforms. For example, the use of large, thin-film mirrors (basically "solar sails") to collect and concentrate sunlight on solar power generation systems is critical to achieving lightweight systems. In addition, the use of carbon nanotubes in composite structures holds great promise to reduce the mass of future SPS platforms.

Safe and Efficient Wireless Power Transmission (WPT)

Safely and affordably transmitting energy from a platform in Earth orbit to a receiver on the ground is essential to the idea of space solar power. The physics of high-efficiency WPT is certainly feasible: Nicola Tesla first articulated the concept of wireless transmission of energy more than 100 years ago and the key component technologies for efficiently sending a coherent beam of electromagnetic (EM) energy over long distances were developed during the 1950s-1960s. There are four characteristics that matter most: the length of the EM waves being used, the distance over which the beam is to be transmitted, the diameter of the transmitter, and the diameter of the receiver.

There are two fundamental approaches to achieving this objective: one that uses a coherent beam of RF energy transmitted at microwave wavelengths (i.e., roughly between 1-10 inches, or between 2-20 centimeters), and the second using a coherent beam at visible or near-visible wavelengths – a laser. The debate among SPS advocates over which technology is "better" has been going on for years.

The advantages of using a laser for beaming power are a result of the extremely short wavelengths involved – the wavelength of near-visible light is roughly 700 nanometers (in other words, $700*10^{-9}$ meters), compared to 1-10 centimeters (i.e., about 0.01-0.1 meters, or 10,000,000-times larger than light!). As a result, lasers enable very small transmitters and receivers, even from GEO (a distance of 22,300 miles (or 35,700 km). For example, a near-visible laser in GEO with an aperture of 12 feet would produce an illuminated spot on Earth of about 120 feet. Unfortunately, lasers have several significant disadvantages, most significantly the relatively low efficiency of the key components involved. Current solid-state lasers have efficiencies of only around 10-15 percent and receiver PV arrays of around 20 percent. The result is that a laser power beaming system using "on-the-shelf" technologies would only achieve an end-to-end efficiency of about 3 percent. However, with expected advances in technology, solid-state lasers could probably achieve efficiencies of about 25 percent, and PV cells that were tailored to match the wavelength of the laser could convert greater than 60 percent of the light received. Even so, this advanced technology system would only yield end-to-end efficiencies of approximately 15 percent. Laser wireless power has the additional problem that the beam cannot pass readily through haze or cloud cover, further reducing the average efficiency.

By comparison, microwave power beaming systems have the potential for much greater component and end-to-end efficiencies, with transmitters approaching today at 40-50 percent, and future technologies expected to reach 70-80 percent, with receivers already at efficiencies of 80 percent or more. As a result, future end-to-end microwave power transmission efficiency should be able to reach better than 60 percent. However, microwaves are much longer in wavelength, requiring a much, much larger diameter transmitter in space and receiver on Earth. For example, a microwave transmitter with a wavelength of about 12 centimeters (i.e., roughly 5 inches) and an aperture of 1,000 meters in GEO would illuminate a spot with a diameter of about 10 km on Earth.

High-Efficiency / Low-Mass Solar Power Generation

It is equally important that the generation of power from incoming sunlight be achieved at high efficiency and very low cost. Conventional solar arrays generate power with an efficiency of around 20%, and prices of approximately \$8-\$10 per watt of power when manufactured in modest quantities. However, special solar cells – known as multi-bandgap cells—are capable of converting much PV of the sun's energy. With such cells, conversion efficiencies of more than 40% have already been achieved, and efficiencies of more than 50% or more should be realized in the next few years.

High-Temperature / High-Efficiency Electronics

Electronics of all types that can operate at high temperatures with high efficiency are equally essential to SSP. For example, beaming 1,000 megawatts of RF power using microwave amplifiers that are only 20% efficient means that 4,000 megawatts of waste heat must be dissipated from the spacecraft. By contrast, RF amplifiers that are 80% efficient could generate the same output power while only producing some 250 megawatts of waste heat—drastically reducing the size and cost of any cooling system. Fortunately, the development of new electronics materials during the past two decades, driven by diverse commercial applications, hold out the promise that such high-temperature and high-efficiency devices can be realized in the coming two decades.

Efficient and Low-Cost Waste-Heat Removal

Finally, it is important to recall that systems in the space environment are essentially operating inside a "vacuum bottle" where cooling only happens as a result of radiative heat transfer (no air: no convection!). Because of this, removing waste heat in an efficient and low-cost manner is absolutely crucial; otherwise, the heat generated by less-than-perfect solar cells and electronics will accumulate and all-too-quickly "cook" the space systems. As mentioned previously, advances in electronics will reduce the waste heat produced while increasing the endurance of key devices (such as amplifiers for wireless power transmission). For the high-power portions of the transmitter (particularly near the center), additional improvements beyond the state-of-the-art are needed. Promising approaches include spacing heat generating components and local active cooling.

Sending the Power Where It's Needed

A great advantage of solar energy from space is that it can be distributed to where it is needed on the Earth below, unlike convention power generators that are fixed in a single location. Of course, solar energy transmitted from orbit must be converted into an appropriate form for use once it reaches the ground. In the case of a microwave beam, that means conversion using a solid state rectifying antenna (known as a "Rectenna") converting the high-frequency alternating current of the RF signal into steady direct current power. (As mentioned previously, in the case of laser wireless power transmission, the energy from the satellite would be converted into voltage by means of special PV cells, tuned to the frequency of the laser to maximize efficiency.)

Another attractive option which has only recently been identified is the use of solar energy from space to directly produce fuels, fertilizers or other useful chemicals. This alternative to generating electrical power for a local grid would assure continuous use of the energy being delivered by the solar power satellite.

Electronically steerable SPS wireless power transmission systems have the remarkable feature that the power they generate may be dispatched more or less on demand to any appropriately prepared location on Earth below their orbital location. Hence, power might be transmitted to the east coast in North America during peak loads in mid-afternoon, then shifted to the Northwest as evening approaches in the east, and finally shifted yet again to a fuel processing plant in the Midwest for overnight operations. Moreover, electronically steerable transmitter arrays could make it possible to share power simultaneously among several locations on Earth all based on delivering optimum power services (and prices). A trick that no purely ground-based approach can perform!

Wild Cards?

As with any new concept, there are sometimes "wild card" alternatives that could fundamentally alter the available options. In the case of SPS, one such "wild card" is the potential use of resources from the Moon or asteroids to manufacture the SPS. This concept was first examined in the 1970s and 1980s when some space advocates viewed the use of space resources as an alternative to achieving very low cost Earth-to-orbit launch. Although manufacturing in space will certainly be critical to the future economic development of space in the farther term, dramatically reducing the cost of space launch is very, very likely to be much easier and cheaper using any technologies that we know of today.

Another wild card that might transform the prospects for solar energy from space is the concept of the "*Star Tram*" – an all-electromagnetic magnetic levitation launch system that could deliver payloads from Earth directly to a transfer orbit, bound for GEO. Conventional gun-type electromagnetic launchers (such as the coil gun or rail gun, known since the 1970s and earlier) "fire" slugs at high accelerations – tens of thousands of times the acceleration of gravity – at which no electronics could survive. However, the *Star Tram* approach launches payloads at low accelerations – only five to 10 times gravity – making possible the launch of integrated SPS components. The real benefit of this approach is the projected cost – perhaps as low as $25 per pound to GEO. This would be a true “wild card” for energy from space.

Various other wild cards might find application in solar power satellites: room-temperature superconductors, perfect antennas using metamaterials, near-human class artificial intelligence, and others. Any of these might be effectively inserted into future space systems; however, they are not critical to making progress now.

The Path Forward

Solar Power Satellites are technically possible, but the technology is <u>not</u> proven and sitting on the shelf. Significant technical challenges must be overcome if these visionary systems are to be realized. Three steps are necessary for real progress to be made toward the vision of solar energy from space. First, rigorous, end-to-end systems analysis studies are needed; detailed considerations of major technology choices must be developed. Second, aggressive and affordable technology experiments are essential. These experiments must complement systems analysis studies, testing assumptions and resolving performance and manufacturing questions. Finally, meaningful demonstrations of SPS technologies must be conducted – leading step by step to validation that solar energy can be delivered from space in an affordable and flexible way. Such steps should readily leverage wild card advances such as those described above (if they occur), but should not and need not be dependent on them; such revolutionary technologies would be useful, but they are not necessary to get started.

SSP studies, experiments and demonstrations must resolve a handful of technical characteristics. First, technology must be proven that can drastically reduce the mass and the cost of solar power satellite systems. Second, the end-to-end efficiency and precision control of wireless power transmission systems must be validated. And finally, the costs of transportation – first from Earth to low Earth orbit (LEO), and then from LEO to GEO – must be significantly reduced. Step-by-step progress in each area must be achieved if SPS are to be realized.

Would such a course make sense? The answer is probably yes. Obviously, any investment in the SPS studies, technology, and demonstrations must compete with alternative investments in other green energy technology options. However, there are several reasons why an investment now in space solar power may be a good idea. First, unlike ground-based solar power, space solar power has the theoretical potential to deliver solar power world-wide, 24 hours a day, in all weather and all seasons; only with a system of this kind can huge amounts of solar power be used in much of the world – driving down greenhouse gas emissions.

In addition, Solar Power Satellites have the potential to deliver solar energy – as needed – directly to developing countries, allowing them to leap-frog decades of investment in electrical grids and conventional power plants that have no long-term future. Finally, the capabilities that would be advanced – reusable space transportation, autonomous in-space operations, cheap and large-scale solar energy, etc. – would transform our future in space, making satellites, space exploration, and space or Earth science goals possible that are now unimaginable.

Novel solutions are essential if growth in new energy supplies is to be realized while at the same time driving down greenhouse gas emissions. The US – and governments around the world – are now making substantial investments in transformational and sustainable energy technologies. Space Solar Power may well be a wild card for global energy that tips the balance in our favor.

The Case for Space Solar Power

It is crucial for the world to identify, develop, and deploy affordable and sustainable new energy sources. This need is driven by a number of factors, including three critical ones: (1) demand for energy to enable economic growth for a still-increasing global population, (2) concerns regarding the long-term accumulation in Earth's atmosphere of fossil fuel-derived greenhouse gases, and (3) the prospect that during the coming decades annual production of petroleum (and possibly other fossil fuels) will peak and begin to decline.

Continuing economic progress will require a four-fold increase in annual energy use by the end of the century. If carbon dioxide (CO_2) emissions into the atmosphere are to be constrained during the same span, by 2100 some 90% of all energy used must be from renewable or nuclear sources. Notwithstanding optimistic claims to the contrary, it does not appear that there is at present a solution to these concurrent challenges.

Substantial renewable energy now comes from hydropower sources, and a much smaller amount from geothermal power; however, these sources remain a modest fraction of the total. Also, a wide variety of aerospace technologies – including photovoltaic arrays, fuel cells, and wind turbines – have been applied during the past three decades in newer renewable energy systems. Certainly, some of these already-existing “green” technologies can be expected to make still larger contributions to meeting long-term energy challenges faced by the global economy. However, these technologies are unlikely to provide the huge amounts of new and sustainable energy that will be needed in the coming decades.

In the late 1960s, Dr. Peter Glaser invented a fundamentally new approach to global energy: the Solar Power Satellite (SPS). As we discussed previously, the basic concept of the SPS is quite elegant – a large platform, positioned in space in a high Earth orbit, continuously collects and converts solar energy into electricity. This power is then used to drive a wireless power transmission (WPT) system that transmits the solar energy to receivers on Earth. Because of its immunity to nighttime, to weather, and to the changing seasons, the SPS concept has the potential to achieve much greater energy efficiency than ground based solar power systems (in terms of utilization of fixed capacity).

In addition to its promise for Earth, Space Solar Power systems could also provide affordable and abundant power in space. Whereas most past space missions have been energy paupers, future missions might be energy rich. The largest commercial communications satellite today operates with no more than 20 kW – about the power used by 5-7 homes in the industrial countries. Even the International Space Station operates with about 100 kW of power. Moreover, the prices paid for the energy used in space today is extremely high, ranging up to almost $100 per kWh (a bit less than 1,000 times more than typical costs in many markets on Earth). It is my view that as long as the power in space is scarce and expensive, nothing ambitious will ever be possible.

SSP has been the subject of numerous systems studies and technology research during the past 40-plus years. These have included several intense but episodic efforts in the US, Canada, and Europe, steady technology research and development (R&D) activities in Japan, and recent activities in China and India. There have been a number of national and international conferences, workshops and symposia addressing the SPS concept. Despite these activities, this visionary idea has failed to become a major part of the space or the energy agenda of any country except Japan.

The Objectives of this Book

The principal objective of this book is to make the case for Space Solar Power; in it, I hope to persuade you that SSP is doable, and that if it were developed it would be immensely valuable for use in space and on Earth. I also hope to convince you that, because of its promise, SSP should be a part of any portfolio of new energy and/or space technology investments. And lastly, I argue that Space Solar Power cannot be a "government only" undertaking. Although government support and international cooperation are essential, by its nature the development of Space Solar Power must involve both researchers in universities for the longer term and entrepreneurs in the private sector to aggressively push the technology forward and to leverage these advances as they are realized.

The book follows a simple narrative line, examining first the need for new energy and reviewing the history of Space Solar Power. It takes a hard look at the shortcomings of past SPS concepts and technologies, and the challenges that remain despite the real progress that has been made in recent years. By way of reaching this objective, a very promising new concept – Solar Power Satellite by means of Arbitrarily Large Phased Array (SPS-ALPHA) – is examined in detail, including not only the concept but also its potential applications in space missions and markets on Earth. SPS-ALPHA appears to be technically feasible and could well prove to be economically viable for missions in space and markets on Earth.

The discussion closes with a proposed Space Solar Power roadmap based on SPS-ALPHA and an assessment of the technologies needed, arguing that the path to those technologies is not only doable but extremely important to humanity's future.

1-1 Each chapter begins, as you will discover, with a relevant quotation; references include, for example: http://www.quotes.net/quote/43593, http://en.wikiquote.org/wiki/Albert_Einstein , etc.

1-2 Space Solar Power (SSP) is the generic term for this technology that has been used for the longest time. It refers to either space applications or systems that deliver energy to markets on Earth. Another term sometimes used for an SSP system that delivers energy to Earth is "Space-based Solar Power" (aka, "SBSP"), which was used by the 2007 assessment performed by the US Department of Defense (DoD) National Security Space Office (NSSO).

1-3 Roughly speaking, at the equator in mid-summer at dawn and dusk, sunlight passes through about 280 miles of "dense" atmosphere (including water vapor, clouds, etc.), while at noon, it only passes through about 10 miles of this kind of air. At local noon, thin clouds reflect less than 20% of the incoming sunlight, whereas heavy cloud cover may reflect over 80% of the incoming sunlight.

1-4 Of course, even conventional power plants require maintenance and repair; a typical estimate of the "availability" of a baseload power plant is around ninety percent (90%). In other words, over one year, a

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conventional baseload power plant is would be available for about 7,889 hours – or about 90% of 8,766 hours in a given year.

1-5 Note that the efficiencies of energy conversion or transmission are not shown in this figure, but they are embedded in the results, such as the comparison of ground area requirements. These calculation details are discussed in a later chapter.

1-6 The concept of the Solar Power Satellite was invented in the late 1960s by Dr. Peter Glaser of the Arthur D. Little company. Some of the details of this and other aspects of the history of SSP are discussed in Chapter 3.

1-7 There are a number of alternatives for almost all SSP system choices; the alternative described here represents a novel concept that has been defined only recently. Descriptions of various different types of SSP concepts as well as advanced modular approach shown here are provided in the chapters that follow.

1-8 The Space Shuttle was intended to be such a vehicle. Unfortunately, the technologies of the 1960s and the cost constraints imposed during the 1970s on the Shuttle development project prevented it from ever achieving true reusability or low cost.

1-9 Feingold, H. et al; "Space Solar Power: A Fresh Look at the Feasibility of Generative Solar Power in Space for Use on Earth" (SAIC; Schaumberg, Illinois; Report NASA SAIC-97/1005; NASA Contract NAS3-26565; Task Order 9). April 4, 1997.

Chapter 2

Economics, Energy, & the Environment: The Context for Space Solar Power

"There is practically no chance communications space satellites will be used to provide better telephone, telegraph, television, or radio service inside the United States."

T.A.M. Craven (1961)
US FCC Commissioner

The Problem We Face

The seven billion people living today use a total of roughly 120,000 billion kilowatt-hours of energy each year, including electricity, transportation fuels, heating, and other purposes. A dozen or so countries use the majority of that energy, and the most energy per person is used by the United States. Affordable and abundant energy is <u>essential</u> to modern society. However, there are challenges on the horizon: (1) competition spurred by growing global populations and surging demand for the energy essential to prosperity, (2) increasing concerns regarding the long-term accumulation in Earth's atmosphere of fossil fuel-derived greenhouse gases, and (3) the prospect that during the foreseeable future global production of fossil fuels will peak and begin to decline.[1] As a result, if society as we know it is to continue during the coming years, then the world <u>must</u> develop, demonstrate, and deploy affordable and sustainable new energy sources.

The aerospace community can contribute to efforts to overcome these challenges. A wide variety of aerospace technologies – including efficient photovoltaic arrays, high energy and low mass fuel cells, and beautifully aerodynamic wind turbines – have in past years been applied in various renewable energy systems. However, although existing "green" technologies can make substantial contributions to meeting long-term energy demand, they are unlikely to provide the huge amounts of continuous baseload power that will be needed in the coming decades. As a result, multiple new technologies are now being researched. Although not well known, one of the most promising and technically challenging of these is Space Solar Power (SSP): the concept of collecting the virtually limitless energy of the sun available in space and delivering it safely and cost-effectively to communities on Earth.

The goals of this Chapter are to establish why novel solutions such as Space Solar Power are needed so badly and to set the stage for the later discussion of SSP markets and economics.

Future Energy Demand

Now and for the remainder of this century there is a tremendous need to identify, develop and deploy new energy sources. This need is driven both by the demographics of Earth's rising population and by the surging affluence of billions of individuals in what have been known as "developing economies" – particularly the more than two billion people who live in India and China. Table 2-1 summarizes some characteristic forecasts of energy and related environmental factors; these are the global energy context for discussing Space Solar Power.

Despite the global "great recession" that began in 2008, economic growth in the coming decades will require increases in the supply of energy worldwide – including energy for primary heating and cooling, for transportation, and especially for electrical power generation.[2] Forecasts vary widely, of course; however, barring a catastrophe (e.g., a world war, major pandemic, etc.), it seems inevitable that the world's population will increase from 7 billion in 2012 to more than 9 billion, and perhaps as many as 12 billion in 2100. At the same time, as shown in Table 2-1, energy use is forecast to become twice the 2012 level by 2030-2040, and four-times that amount by 2090-2100. Delivering these huge increases will require massive development of new power plants as well as new sources for transportation fuels and other energy sources.

Table 2-1 Current Day (2012) and Forecast Energy/Environment Factors[3]

		2012	2030-40	2060-70	2090-2100
Global Population	High	~ 7 billion	~ 9 billion	~ 11.5+ billion	~ 12.5+ billion
	Medium	~ 7 billion	~ 8.5 billion	~ 9+ billion	~ 8.5+ billion
	Low	~ 7 billion	~ 7.5 billion	~ 7+ billion	~ 5.5+ billion
Current / Projected Global Annual Energy Consumption[4]		~120,000 Billion kWh	~220,000 Billion kWh	~400,000 Billion kWh	~480,000 Billion kWh
Low Renewable Energy Case	Renewable Energy: Low Share Case [5,6]	~10%	~10%	~10%	~10%

		2012	2030-40	2060-70	2090-2100
	IPCC Projection: High CO_2 Emissions Case [7,8]	~31 bn MT/year	~55 bn MT /year	~100 bn MT /year	~125 bn MT /year
High Renewable Energy Case	Renewable Energy: High Share Case	~10%	~50%	~70%	~90%
	IPCC Projection: Low CO_2 Emissions Case	~31 bn MT /year	~28 bn MT /year	~22 bn MT /year	~15 bn MT /year

Historically, energy use has been both an enabler and a strong indicator of both wealth and the quality of life in a society. At present, humanity uses about 120,000 billion kWh of energy each year, about 85% of which is derived from the combustion of fossil fuels (including coal at roughly 29%, oil at about 33% and natural gas at some 23%).[9] In the US, Japan, European countries and Canada, annual consumption of energy of all types per capita is roughly 60,000 kWh/person-year (i.e., kilowatt-hours per person per year).[10] However, the global average energy use per person is only about 17,000 kWh/person-year – more than a 3-fold difference. By 2100, global per capita energy use is projected to reach about 38,000 kWh/person-year, an increase of more than double the current annual energy use per person. Even so, at the end of this century, global energy use would still only average about 50% of today's usage in US and the other wealthy countries mentioned previously.

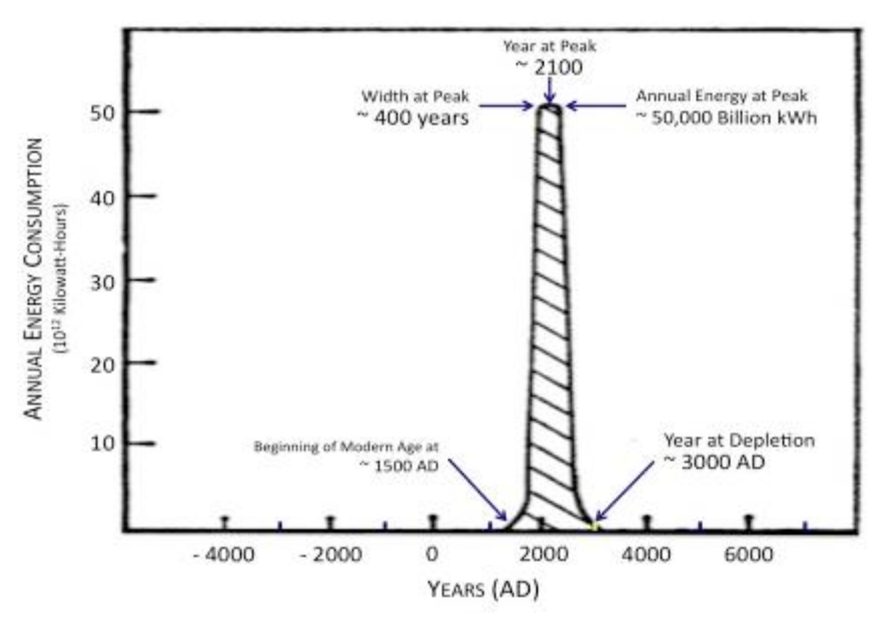
In summary: barring a disaster on a global scale, the world's population will increase dramatically by the end of this century and those billions of people will want a much, much higher quality of life (requiring much greater use of energy) than the world average today To meet this growing demand, vast new energy supplies are needed by 2100 – perhaps as much as 400% of today's total. Where will this energy come from? For more than 150 years, global economic growth has been powered almost entirely by fossil fuels; but that is unlikely to continue to be possible for two reasons: the threat of climate change, and the limits of fossil fuels.

Peak Fossil Fuel Production

Complicating the challenge of planning for future energy resources and investments appropriately is the difficulty of anticipating when production peaks for various fossil fuels may occur. In 1956, an American geophysicist, M. King Hubbert, observed that over time fossil fuel production in any given geographical region must follow a roughly bell-shaped curve derived from the "logistic curve".[11] By extension, the same must be true for Earth as a whole: all of the fossil fuel in the world – from oil wells, natural gas fields, or coal mines – is finite, and must ultimately be exhausted. Moreover, the course of fossil fuel consumption can be predicted; all of the individual bell-shaped curves add together to become a single overarching bell-shaped forecast for the entire world.

As it happened, Dr. Peter Glaser made a visionary reference to this forecast in his seminal 1968 SPS paper, and illustrated the point with a simple yet troubling figure that plotted the consumption of fossil fuels from the dawn of recorded history to roughly the present, and then forward to a point in time equally distant in the future. An annotated version of the graph is presented in Figure 2-1. The entire graph is flat to the left and to the right of the center point – approximately the present – and at that point there is a sharp spike of energy consumption 300-400 years wide (about 150 years before today, and about the same length of time afterward). This spike represents the entirety of the opportunity that humanity has at hand: a single chance to exploit the sustainable power sources found in nature (i.e., sun, wind, water, the atom and biomass), or else drop back into the darkness of pre-history.

Figure 2-1 Annotated Hubbert Curve from Glaser's 1968 *Science* Paper



The so-called "Hubbert Curve" illustrates the fact that petroleum is a finite resource, and that in any given locality, and for the world as a whole, production must peak at some point in time; after that production peak, the annual amount of the fuel that is available for use can only decline. Moreover, other fossil fuels (i.e., coal and natural gas) must also follow these statistics and have natural production peaks and expected declines. The question of the timing of when such peak production may occur is, not surprisingly, extremely controversial.

For the past 200 years – beginning with the writings of Malthus – pessimistic scholars have from time to time warned society that the "limits to growth" were fast approaching and that further increases in human population and consumption could not be sustained. [12] In the 1950s, when the "Age of Oil" was about a century along, Hubbert applied statistical analysis techniques to make a similar prediction regarding oil. So far, these "doom-sayers" have been proven wrong: new technologies have been developed and new resources discovered just when they've been needed, and the growth in humanity's population and wealth have continued. Are we now correct in ignoring predictions of exhausted resources (fossil fuels in particular) as a looming risk to society?

There is a well-known children's story about the "boy who cried wolf." In it, a young man became bored with watching his village's flock of sheep and decided to play a prank. He shouted to his family and friends that a wolf was attacking the flock. Everyone came to help, but there was no wolf. The boy enjoyed the affair immensely and – despite being punished for the false alarm – proceeded to do same thing again and again. In due course, the young man's family and other villagers stopped listening. Unfortunately for the boy, shortly afterwards a pack of wolves actually did appear and, despite his frantic cries for help, no one came. The boy – and we must assume many sheep – were devoured.

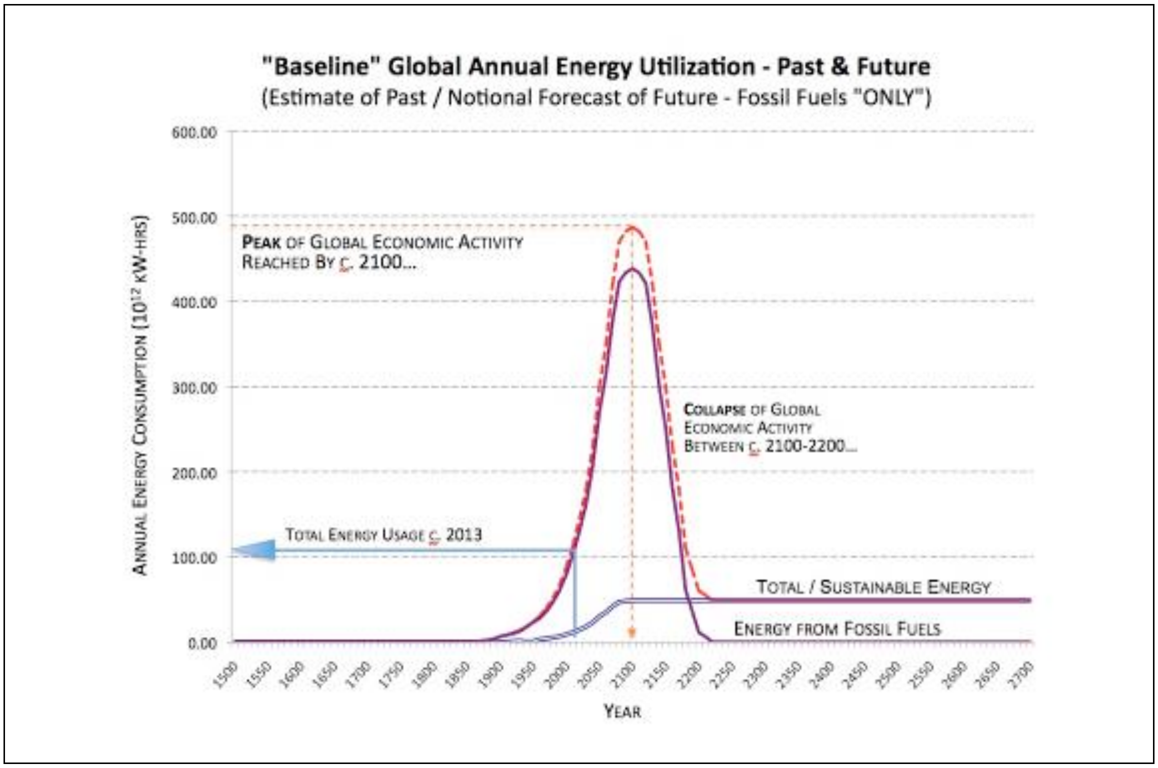
Just in the past handful of years, new technologies (fracking and horizontal drilling) have opened to commercial development previously inaccessible reserves of natural gas and oil. The new sources of natural gas in particular are immensely valuable, leading to significant new industrial activity and at far lower environmental impact than the use of similar amounts of energy from oil or coal would bring. However, all of the new reserves of natural gas now being developed will also one day be depleted: as the world's population continues to increase and global economies grow, so too will the rate at which these new sources of gas and oil are consumed. As mentioned above, just when global supplies will fall permanently behind global demand is the most important and the most controversial question.

There are two basic schools of thought about this question.[13] The first argues that the new "tight" gas and oil fields will behave more or less like traditional fields, yielding fuels for many years once production starts. The second group points to production data concerning early examples of gas fields involving fracking (i.e., "hydraulic fracturing") and horizontal drilling, which show unusually rapid depletion of those fields. If the former projections are right, then the new sources of gas won't peak for several decades. If the latter prove correct, then the boom in production now driving down prices is in fact a "bubble" and will be followed by the collapse of all existing fracking-based wells.

Why in the world spend so much time on this topic in a book about solar power from space? The answer is simple: the overall global marketplace for energy during the coming decades – including resources and climate issues – is essential to making the case for Space Solar Power. For the purposes of this discussion, I decided to take as a baseline the most optimistic point of view, namely that fossil fuels – including those obtained through new technologies – wouldn't be severely depleted until the end of this century. Figure 2-2 presents this hypothetical projection of when, and at what level, peak fossil fuel production will occur. This version of the Hubbert Curve is based loosely on a similar figure from Dr. Glaser's original 1968 paper (Figure 2-1), updated with current data on the rate of growth to the present and the total amount of fossil fuel available. This version of the curve begins at around 1500 AD – roughly the beginning of the modern world – and is centered not on the present but at a point roughly 100 years in the future when the total production of fossil fuels may be expected to peak, based roughly on the total reserves (known and expected) of these fuels. This baseline makes a simple assumption: fossil fuels are consumed as fast as economically advantageous, without regard to their depletion or other (e.g., climate) consequences.

All credible authors now accept that fossil fuels will eventually be depleted; the question is when it will happen. Of course, no one knows for certain when the production of different fossil fuels will peak; however, generally speaking, this date is now expected to be earlier for petroleum and later for coal and natural gas. Even in the case of the latter fuel, there is great uncertainty as to when peak production may be reached. At current levels of consumption (c. 2013), oil is expected to be severely depleted within 40-50 years, coal within 100 years, and natural gas within 100-200 years.[14] However, as just discussed, today's level of energy use will not continue; consumption is projected to increase by approximately four-fold by the end of this century, from about 120,000 billion kWh per year to about 480,000 billion kWh per year.

Figure 2-2 Baseline Forecast: Future Peak Fossil Fuel Production[15] (Scenario "Zero")

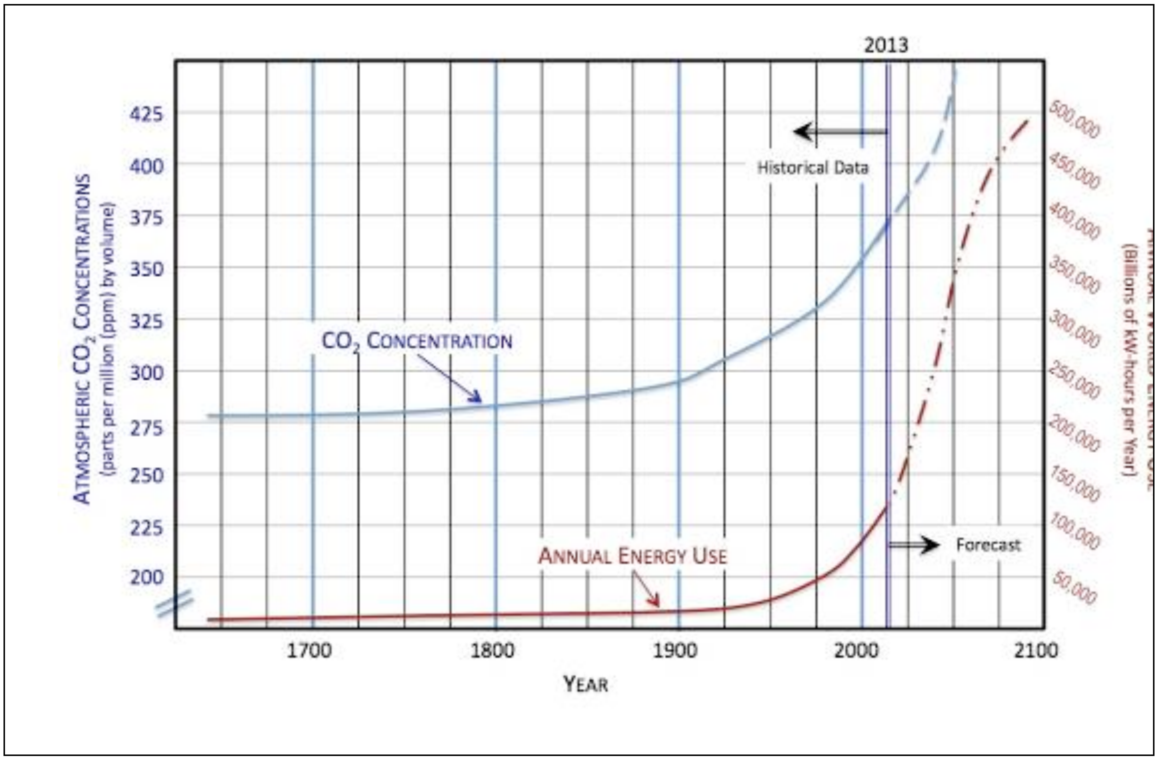


Credit: Artemis Innovation Management Solutions LLC (2013)

Another Factor: CO_2 Emissions and Climate Change

Annual energy usage has been growing steadily throughout most of the past two centuries. And there is no doubt that the concentration of Carbon Dioxide (CO_2) in Earth's atmosphere has been growing; numerous measurements from locations around the world have confirmed this fact. As it happened, the first measurements of atmospheric CO_2 concentrations were made at the US National Oceanographic and Atmospheric (NOAA) research station near the summit of Mauna Loa in Hawaii. There is a bronze plaque commemorating this accomplishment on the wall outside the entrance to one of the older building at the site. Coincidentally, in 2008 and 2010, this NOAA research station kindly accommodated testing of wireless power transmission (WPT) for future Space Solar Power between Mauna Loa on the big island of Hawaii and Haleakala 140-plus kilometers away on the island of Maui.[16] Figure 2-3 presents a synthesis of the measured atmospheric CO_2 concentrations in the air, and increasing annual energy use over the past two hundred years, up to the present day (c. 2013).

Figure 2-3 History of Annual CO_2 Atmospheric Emissions & Concentrations[17]



Credit: Artemis Innovation Management Solutions LLC (2013)

There is still some debate among policy-makers within the US as to whether or not the increases in CO_2 are caused by humanity, and whether or not increasing CO_2 concentrations are causing global climate change. However, there is no debate among the vast majority of scientists; they regard both propositions as overwhelmingly likely to be true.

A large group of international climate scientists working as the Intergovernmental Panel on Climate Change (IPCC) has developed more than three-dozen analytical scenarios for CO_2 emissions that portray different patterns for future events, ranging from (a) continuous increases in emissions (at varying rates) up to the year 2100, to (b) emissions that incrementally level off by 2100, to (c) reversals in CO_2 emissions trends in which they start to decline between 2050 and 2100. These alternatives depend greatly on the detailed assumptions made in each case – and in particular the choices we make <u>now</u> regarding energy.[18]

At present there are <u>no</u> possible policy solutions to meeting the global challenge represented by the risk of climate change during the remainder of this century. New energy sources are essential for prosperity, and only new, carbon-neutral energy solutions – so-called "sustainable energy" solutions – on a vast scale will suffice. Dr. Martin (Marty) Hoffert and a team of co-authors made this point in an important 2002 paper published in the journal *Science*.[19] This simple fact is the reason why Space Solar Power might be of great significance – if it can be developed successfully and SPS power delivered from satellites at an affordable (i.e., market competitive) price.

Assessment of the Global Challenge

Conclusions may be drawn from the global economics, energy, and environmental context described above. First, it will be impossible for the projected population of Earth to realize a high quality of life without huge increases in total energy use during the remainder of this century. In other words, the annual energy needed to assure economic opportunity for an increasing fraction of Earth's growing population will not be provided without massive deployment of new power generation capacity and other forms of energy utilization (e.g., transportation, primary heat / cooling, etc.). However, our current reliance on fossil fuels to provide this energy cannot be expected to do the job indefinitely: eventually, reserves will become depleted. Moreover, the environmental impact that may be caused by these increases in energy consumption will depend directly on the sources of energy we use; only dramatic advances in the technologies used to deliver that energy can mitigate CO_2 emissions.

In the absence of other factors (for example, unexpectedly early peaking of fossil fuel production), it is evident that radical changes in the energy mix will be needed – not just by the end of the century, but within the next two or three decades. To realize the low-end of CO_2 emissions goals, the total amount of energy delivered by carbon-neutral sources must increase from roughly 12,000 billion kW-hours per year in 2010, to more than 110,000 billion kWh per year in 2030-2040, and to more than 430,000 billion kW per year by 2100.

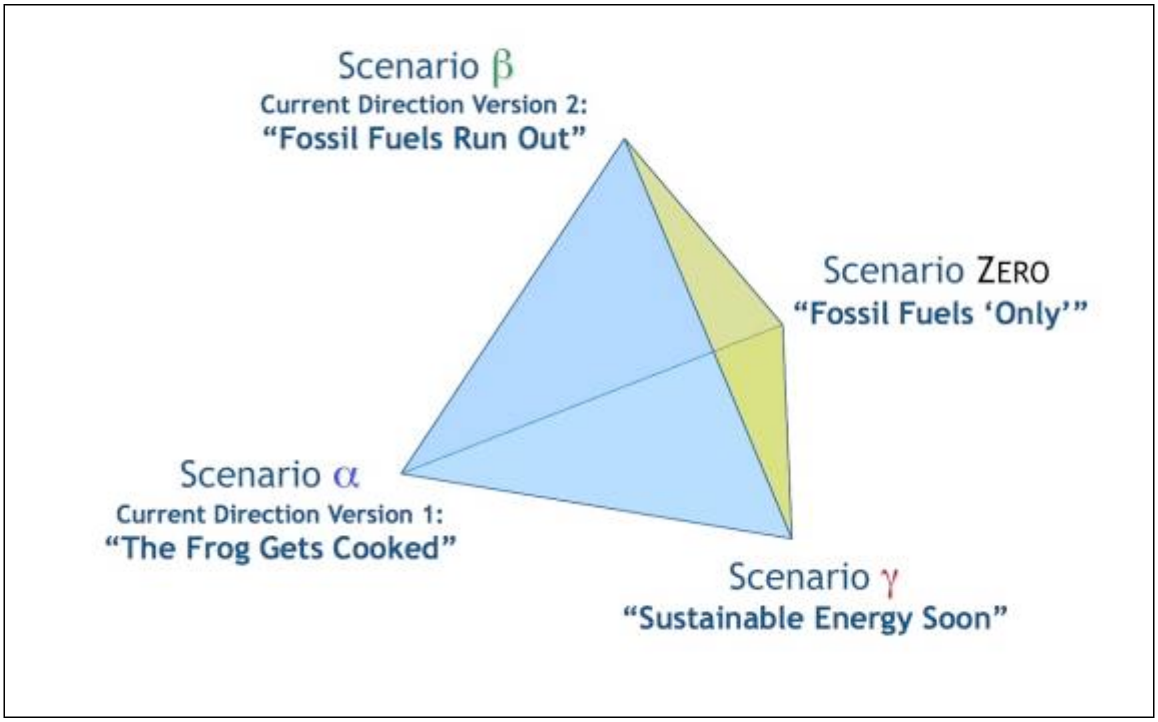
Fortunately for climate change concerns, something remarkable has happened in the past 4-5 years: vast new reserves of natural gas have become available – particularly in North America – because of the new extraction method known as "hydraulic fracturing" (i.e., *fracking*) for natural gas. When used in modern systems, such as combined cycle power plants (CCPP), natural gas releases only about half the carbon dioxide per kilowatt-hour produced compared to the combustion of the coal, and generally yields fewer air pollutants. Moreover, natural gas can also be transformed using techniques known as “gas-to-liquids” (GTL) processing to produce liquid fuels (e.g., methanol or synthetic crude oil).

This is not to say that *fracking* is uncontroversial within the environmental community; this process involves several unresolved risks such as causing local ground water contamination, releasing GHG into the air, and others. And, even given the vast new reserves that fracking makes available, eventually fossil fuels will still become depleted. What this revolution means, however, is that there is now more time before the energy availability and security issues described become acute. Low-cost natural gas, developed and deployed for power generation and fuels, may prove to be an essential bridge from today’s energy mix, which is still heavily reliant on the burning of coal, to one that is sustainable and scalable for the future.

Framing the Question of SSP: Strategic Global Scenarios

For more than a decade, the IPCC has labored to frame detailed model-based forecasts of greenhouse gas (GHG) emissions and accumulations in the atmosphere, as well as resulting changes in Earth’s climate. The result is a broad array of curves, which can be challenging for the non-expert to understand.[20] As cited in the previous chapter, in order to more simply frame specific market cases and architectures for Solar Power Satellites, the 2008-2011 International Academy of Astronautics (IAA) study formulated four high-level scenarios for the global future of energy and the environment during the remainder of this century. Here, I have chosen to follow the general IAA template, but with greater detail in terms of the four modified scenarios as illustrated in Figure 2-3: (1) Scenario **Zero** – optimistic projections for fossil fuel depletion, but minimal new technology options; (2) Scenario **Alpha** – “Business as Usual – the Frog Gets Cooked”; (3) Scenario **Beta** – “Business as Usual – Fossil Fuels Run Out Early”; and (4) Scenario **Gamma** – “Sustainable Energy Technologies Emerge.”

Figure 2-3 Global Energy / Economic Scenarios for SSP



Credit: Artemis Innovation Management Solutions (2013)

The scenarios will be discussed in more detail in a moment. By way of an introduction, it is important to note that these scenarios suppose (1) that the current scientific consensus regarding greenhouse gas (GHG) emissions and global climate change is correct (namely, that human-caused increases in the atmospheric concentrations of GHG are responsible for observed changes in global climate over the past several decades); and (2) that our current understanding of the types and amounts of fossil fuel reserves – both known and predicted – is essentially correct. Given these assumptions, the following are the key questions that the scenarios examine.

What might happen if we are right about the science of climate change and about the available reserves of fossil fuel, but do nothing more (beyond what is now being done vis-à-vis new energy sources)? This is Scenario Zero.

What might happen if we are wrong about the severity of climate change that may occur during the coming century; i.e., what if these changes are faster and worse than expected? This is Scenario Alpha.

What might happen if we are wrong about the severity of climate change that may occur during the coming century; i.e., what if there is only about half the levels we believe to exist? This is Scenario Beta.

And, finally, what might happen if we move more aggressively and successfully to develop and deploy sustainable energy options, such as SSP? This is Scenario Gamma.

The following paragraphs elaborate each of these global scenarios.

Fossil Fuels "Only" with Minimal New Technology (Scenario Zero)

"Scenario Zero" is the baseline situation that we now face. In addition to the assumptions indicated above, it presumes that there are no significant actions being currently taken to prepare for the eventual and inevitable depletion of fossil fuels that provide a significant majority of the energy used by society today. This scenario accepts that the science of climate change and of fossil fuel geology are accurate, but supposes that current efforts will not be augmented or accelerated, and hence that carbon-neutral energy sources will grow no faster than the growth in fossil fuel consumption during the coming century. Most important: this scenario assumes that the *Hubbert Curve* and related projections are correct and that there will be upper limits to the maximum annual production of key fossil fuels. Figure 2-2 illustrates this scenario.

The figure shows the historical fact that significant increases in global energy use began approximately around 1850 with the ramping-up of the industrial revolution. It also illustrates that current use of energy is somewhat more than 100,000 billion kWh per year and the maximum production of all fossil fuels at about 480,000 billion kWh may occur around approximately 2100. After that point, the aggregate production of energy from fossil fuels declines more or less symmetrically with the prior growth in production; however, because the use of non-fossil energy sources rose to about 10% of the maximum in 2100, the total production does not fall below that amount. Hence, global energy use stabilized after the collapse of oil production at about 50% of total production today, i.e., at around 1950-1960 levels.

In the case of Scenario Zero, there are modest but no really significant markets for new energy sources until the world gets closer to the decline of fossil fuels around 2100. This is far enough off in the future that potential markets for Space Solar Power are also modest in scale (other than space applications and premium markets, discussed in Chapter 10 and Chapter 11, respectively).

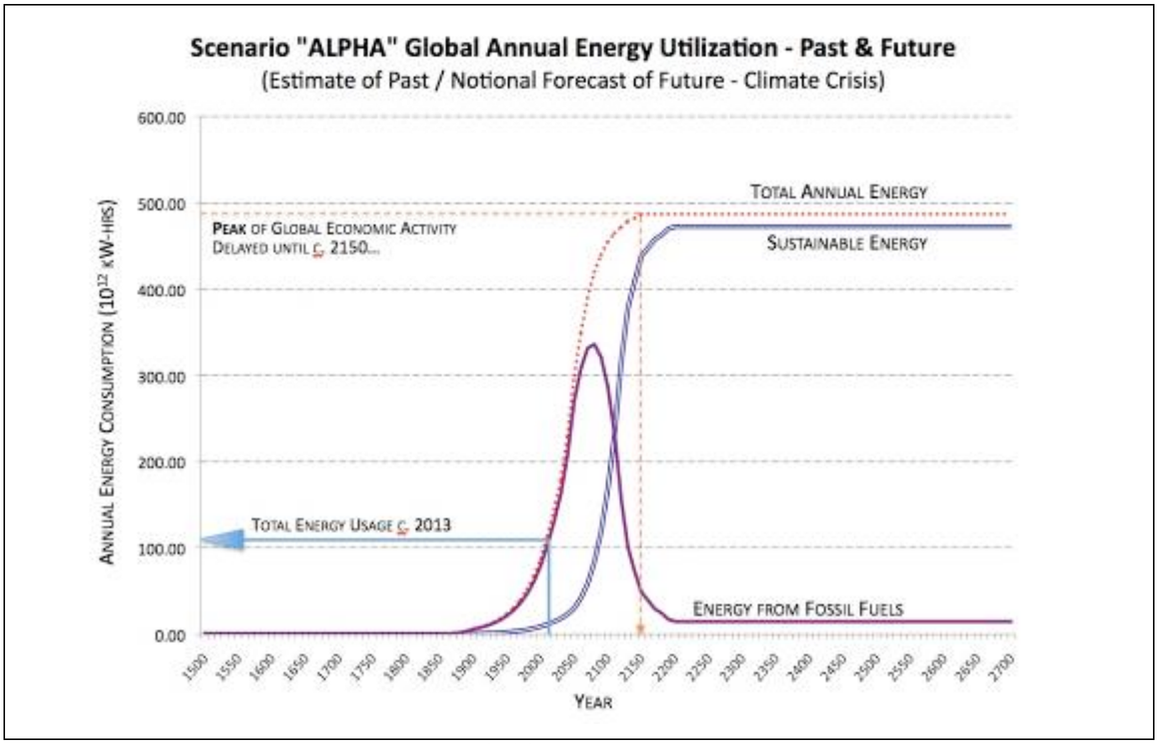
“Climate Crisis” (Scenario Alpha)

There is an old folk tale about the right way to make soup from frogs. (First, you must catch the frogs!) If you drop the frogs into a pot full hot water, they will immediately perceive their danger and jump out of the pot to safety. However, if you place the frogs in a pot of cool water and slowly bring it to a boil, the frogs will never perceive the danger – and soon enough you will have frog soup! In the case of this first scenario that begins from the basis of “business as usual,” we are the frogs.

Scenario Alpha postulates that there is no acceleration of current day (c. 2013) national and international policies to develop new, more sustainable energy sources while increasing the efficiency with which we use all energy sources. As a result, CO_2 emissions grow steadily over the next four decades – resulting in gradual but significant increases in GHG concentrations and in Earth’s temperature. Figure 2.4 illustrates the energy mix and level for this scenario.

Also, this scenario supposes that principal fossil fuels – in particular, coal – do not start to run out starting around mid-century. In this case, huge numbers of additional coal-fired power plants are constructed and continue to operate until well into this century – dramatically increasing atmospheric levels of GHG. There are modest to minimal advances in technology that are driven by the goal of reducing GHG emissions, but these occur only slowly. During the first half of the century, there are significant increases in GHG, and depletion of fossil fuels only begins to occur late in the century. Scenario Alpha anticipates significant increases in GHG emissions, and that the worst-case projected temperature increases will occur as a result.

Figure 2-4 1,000-Year Energy Scenario Alpha: "Climate Crisis"



Credit: Artemis Innovation Management Solutions LLC (2013)

Because of these developments, in this scenario there are drastic global impacts due to climate change. In addition, because of the resulting changes in the climate, there is meaningful destabilization in global economies and international relations. International competition for fossil fuels becomes fierce, sea level rises, and extreme weather becomes commonplace – resulting in rising geopolitical tensions, occasional conflicts, and increasing energy prices. As a result, beginning around mid-century, the changes in climate finally drive major new investments in sustainable energy technologies. Key aspects of this scenario include:

Minimal investments are made during the coming decade in new, more-sustainable Energy Technologies.

There are stable, (delete) but steadily increasing prices for conventional energy due to international competition for resources.

Significant increases in the net price of fossil fuel-based energy occur due to market forces, primarily later in the century.

There are enormous increases in GHG and the resulting global climate change through the end of the century is beyond the high end of current projections.

Peak global production of fossil fuels occurs as follows:

- Petroleum → peaks in 2020-2030
- Natural Gas → peaks in 2080-2100
- Coal → peaks post 2100

Electrical Power Generation (early in the century):

- Primary Commercial Baseload Electrical Power @ roughly the same as 2013 (e.g., approximately 5¢-10¢/kilowatt-hour)
- Remote / Leveraged Commercial Baseload Electrical Power @ roughly the same as 2013 (e.g., approximately 25¢-50¢/kilowatt-hour)
- Premium Niche Market Electrical Power @ at roughly the same as in 2013 (e.g., approximately $2.00-$2.50 /kilowatt-hour)

Electrical Power Generation (late in the century):

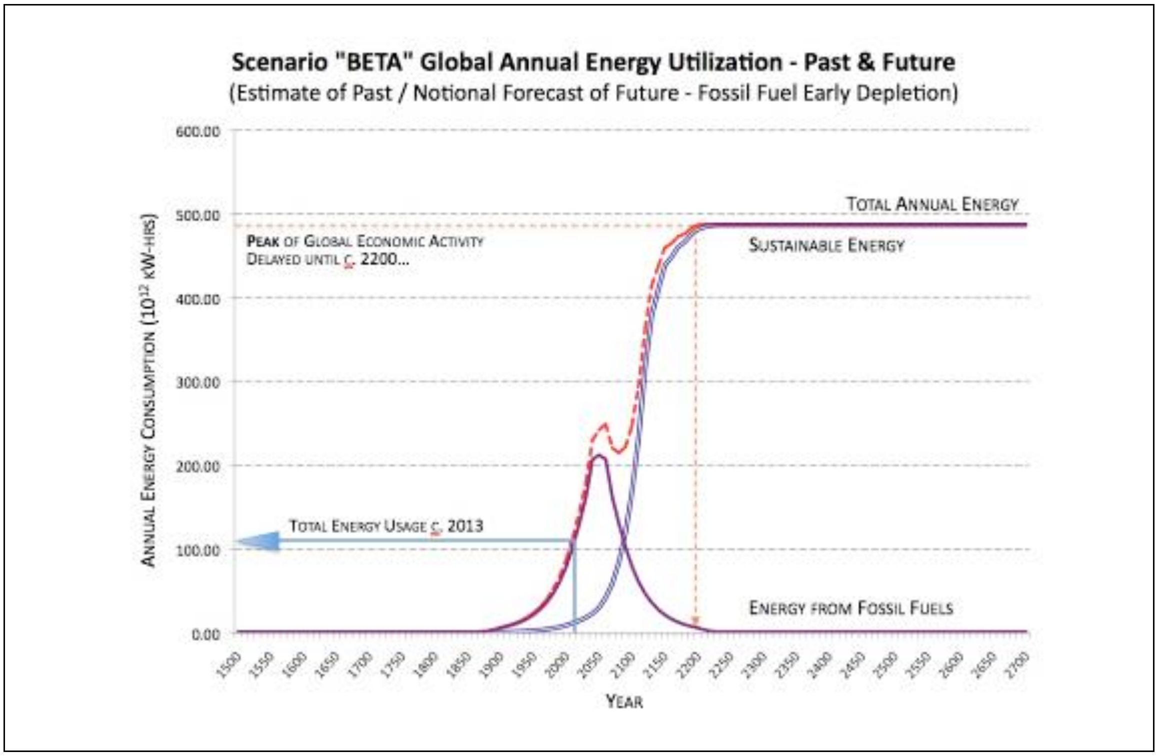
- Primary Commercial Baseload Electrical Power @ much higher than in 2013 (e.g., about 15¢-30¢/kilowatt-hour)
- Remote / Leveraged Commercial Baseload Electrical Power @ higher than 2013 (e.g., approximately 75¢-$1.50/kilowatt-hour)
- Premium Niche Market Electrical Power @ much more than 2013 (e.g., roughly $6.00-$8.00 /kilowatt-hour)

“Fossil Fuels Run Out” (Scenario Beta)

This scenario postulates the near term adherence of “business as usual” policies and failure to accelerate the development of new, more sustainable energy technologies while increasing the efficiency with which we use all energy sources. Instead, this scenario accepts that the issues are real, but supposes that efforts now underway will bear fruit too late. Figure 2-5 illustrates this scenario.

Some advances will occur, of course, and these will have some modest impact on the goal of reducing GHG emissions, but the reductions in fossil fuel use will not keep up with dramatic growth in ongoing fossil fuel consumption. Most important: this scenario supposes that the *Hubbert Curve* and related projections are correct, but that estimates of fossil fuel reserves are wrong, and early depletion of these reserve leads to a massive shock to the global economy and “crash efforts” to develop new sustainable energy options.

Figure 2-5 1,000-Year Energy Scenario Beta: Early Fossil Fuel Depletion



Credit: Artemis Innovation Management Solutions LLC (2013)

As a result, in this scenario the significant depletion of all fossil fuels occurs at about the mid-point of this century. This scenario – "Fossil Fuels Run Out" – anticipates that GHG emissions will continue to grow rapidly until mid-century, and that they will begin to decline only once fossil fuels are depleted. However, as fossil fuels peak (and the markets clearly see that peaking will occur), then market prices for energy go up and stay up. Because of these future events, in this Scenario it is postulated that there are both global climate change impacts due to past GHG accumulations and there are drastic increases in energy prices, starting at about halfway through the century. Key aspects of this scenario include:

There are some investments in new, more-sustainable energy technologies, but these R&D investments are only partially successful.

There are selected policy-driven regulatory changes, including modest mileage standards, some legislative requirements for increasing percentages of carbon-neutral energy, etc.

After the first several decades, rapid and significant increases occur in the wholesale price of fossil fuel-based energy due to market demand as the supply of fossil fuels begins to decline dramatically.

Peak global production of fossil fuels occurs as follows:

- Petroleum → peaks prior to 2010
- Natural Gas → peaks in 2030-2040
- Coal → peaks in 2060-2070

Electrical Power Generation (early in the Century):

- Primary Commercial Baseload Electrical Power @ higher than in 2013 (e.g., approximately 10¢-20¢/kilowatt-hour)
- Remote / Leveraged Commercial Baseload Electrical Power @ higher than in 2013 (e.g., approximately 50¢-$1.00/kilowatt-hour)
- Premium Niche Market Electrical Power @ higher than in 2013 (for example, approximately $4.00-$5.00 /kilowatt-hour)

Electrical Power Generation (late in the Century):

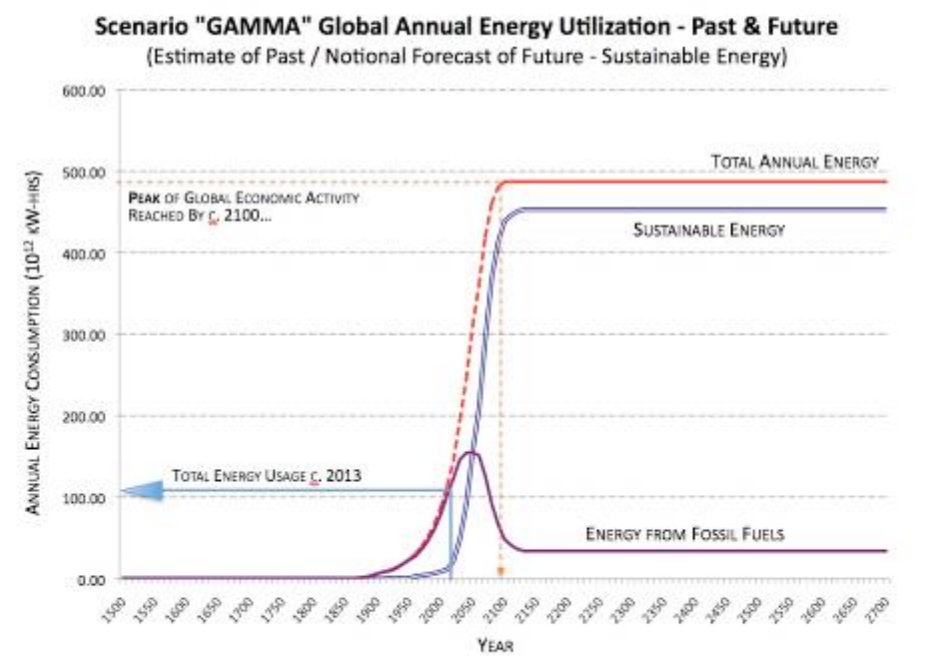
- Primary Commercial Baseload Electrical Power @ much more than 2013 (for example, approximately 40¢-50¢/kilowatt-hour)
- Remote / Leveraged Commercial Baseload Electrical Power @ much more than 2013 (e.g., approximately $1.00-$2.00/kilowatt-hour)
- Premium Niche Market Electrical Power @ much more than 2013 (e.g., roughly $8.00-$10.00 /kilowatt-hour)

"Sustainable Energy Early" (Scenario Gamma)

Scenario Gamma postulates a highly positive outcome for current national and international efforts to define policies and investments to develop new, more sustainable, energy sources while increasing the efficiency of current systems. These advances are driven by the goal of reducing GHG emissions, and occur before any significant depletion of fossil fuels occurs. Figure 2-6 illustrates the overall energy forecast for this scenario.

Because of these assumptions about early investments in new energy solutions, the introduction of non-fossil fuel sources proceeds at a much faster pace, the growth in fossil fuel consumption is much slower, and the peak consumption is much lower. The seemingly contradictory result is that significant levels of hydrocarbon utilization would continue for far longer into the future than would be the case in either of the other two major scenarios (Alpha or Beta). The reason is simple: hydrocarbon fuels are immensely valuable for power production, as transportation fuels, and as feedstock for commodity chemicals (such as fertilizers); if we don't consume them in the next several decades, they will be available later.

Figure 2-6 1,000-Year Energy Scenario Gamma: Sustainable Energy Emerges



Credit: Artemis Innovation Management Solutions LLC (2013)

And, because of the developments described above, in this scenario there are more modest global climate change impacts due to past GHG accumulations. Key aspects of this scenario include:

- There are substantial Investments in new, more-sustainable Energy Technologies, and these R&D investments are fully successful.
- Policy-driven regulatory changes are made, including high mileage standards, legislative requirements for increasing percentages of carbon-neutral energy, etc.
- Significant increases occur in the net price of fossil fuel-based energy due to market based and regulatory actions.
- Peak global production of Fossil Fuels occurs as follows:
  - Petroleum → peaks in 2010-2015
  - Natural Gas → peaks in 2040-2050
  - Coal → peaks in 2060-2070 (driven by technology substitution)
- Electrical Power Generation (early in the Century):

- Primary Commercial Baseload Electrical Power @ more than 2013 (e.g., approximately 8¢-15¢/kilowatt-hour)
- Remote Commercial Baseload Electrical Power @ more than 2013 (for example, roughly 35¢-75¢/kilowatt-hour)
- Premium Niche Market Electrical Power @ about the same as 2013 (e.g., approximately $2.00-$2.50 /kilowatt-hour)

Electrical Power Generation (late in the Century):

- Primary Commercial Baseload Electrical Power @ somewhat more than 2013 (for example, 10¢-20¢/kilowatt-hour)
- Remote Commercial Baseload Electrical Power @ somewhat more than 2013 (e.g., about 50¢-$1.00/kilowatt-hour)
- Premium Niche Market Electrical Power @ about the same as 2013 (e.g., roughly $4.00-$5.00 /kilowatt-hour)

Strategic Scenarios Summary

The scenario-based assessment presented here provides interesting general insights into the potential markets in which SPS-delivered energy would be required to compete during the coming century – and at what types of price points. Table 2-2 provides a summary of the overall framework formulated here. The following are thumbnail summaries of the four scenarios.[21]

Scenario Zero. You may notice that, in the case of "Scenario Zero," fossil fuels begin to be depleted before the emergence of significant levels of new energy resources, and that around 2100 global economic activity begins to collapse – dropping by 2200 to levels of economic activity not seen since the 1950s-1960s. Such a collapse would likely necessitate a drastic reduction in the global population by at least 50%-60%, (and perhaps as much as 70%-80%) from the predicted level of 11-12 billion by 2100.

Scenario Alpha. In this case, we assume that anthropogenic (human-caused) climate change will be more rapid and the consequences worse than consensus scientific predictions of today. In Scenario Alpha, it is "business as usual" for the next 2-3 decades, and then urgent steps must be taken to develop and deploy new, sustainable energy resources.

Scenario Beta. This scenario begins once again with "business as usual"; however, global supplies of fossil fuels are depleted faster than now predicted. Around the middle of the century, energy prices rise significantly, driven by scarcity rather than policy.

Table 2-2 Summaries of Scenarios and Resulting Market Assessment[22]

				Electrical Power Markets Forecast ($/kW-hour)		
Scenarios	**Fossil Fuels Production[a] Peaks Occur**	Policies		Primary Baseload Markets	Niche and/or Carbon-Incentive Commercial Markets	Security-Related Premium Niche Markets
Zero: *“Business as Usual Works Out”*	Oil c. 2050 Gas c. 2100 Coal post-2100	**Early <2030**	Local Carbon Incentives Modest R&D	5¢-10¢ per kW-hr	25¢-50¢ per kW-hr	$2-$2.50 per kW-hr
		Mid ~2060	Local Carbon Incentives Modest R&D	~No Change vs Early	~1.5-times increase vs Early	~1.5-times increase vs Early
		Later >2060	Increasing Carbon Incentives Increasing R&D	~1.5-times increase vs Early	~1.5-times increase vs Early	~1.5-times increase vs Early
Alpha: *“The Frog Gets Cooked”*	Oil c. 2050 Gas c. 2070 Coal c. 2070	**Early <2030**	Local Carbon Incentives Modest R&D	5¢-10¢ per kW-hr	25¢-50¢ per kW-hr	$2-$2.50 per kW-hr
		Mid ~2060	Increasing Carbon Incentives Significant R&D	~1.5-times increase vs Early	~1.5-times increase vs Early	~1.5-times increase vs Early
		Later >2060	Global Carbon Incentives Significant R&D	~2-times increase vs Early	~2-times increase vs Early	~2-times increase vs Early
Beta: *“Fossil Fuels Run Out”*	Oil c. 2030-2050 Gas c. 2030-2050 Coal c. 2070	**Early <2030**	Local Carbon Incentives Modest R&D	10-20¢ per kW-hr	50¢-$1 per kW-hr	$2-$2.50 per kW-hr
		Mid ~2060	Increasing Carbon Incentives Significant R&D	~2-times increase vs Early	~2-times increase vs Early	~2-times increase vs Early
		Later >2060	Global Carbon Incentives Significant R&D	~3-times increase vs Early	~3-times increase vs Early	~3-times increase vs Early
Gamma: *“Aggressive Energy*	Oil c. 2040-2050 Gas c. 2040-2050	**Early <2030**	Increasing Carbon Incentives Significant R&D	8¢-15¢ per kW-hr	35¢-75¢ per kW-hr	$2-$2.50 per kW-hr

Innovation”	Coal c. 2030-2040	**Mid ~2060**	Global Carbon Incentives Significant R&D	~1.5-times increase vs Early	~1.5-times increase vs Early	~1.5-times increase vs Early
		Later >2060	Global Carbon Incentives Significant R&D	~2-times increase vs Early	~2-times increase vs Early	~2-times increase vs Early

[a] The projected peaking of fossil fuels projection may be attributed to either depletion of available resources or to policy steps

Scenario Gamma. I suspect that this might be the least likely of the scenarios; it assumes that timely decisions are made to mitigate both the risks of climate changes and of fossil fuel depletion. However, this is probably the most attractive scenario for SPS-supplied power in the nearer term (because of the prospect for significant government-sponsored R&D).

Closing Observations

Issues involving energy, the environment, and global economics will be prominent in national and international politics and economics throughout this century. A high-level scenario-based approach such as that discussed here obviously does not reflect in-depth simulation or modeling of markets or prices. However, the approach can synthesize the differences at a conceptual level among the scenarios in terms of energy prices in markets of interest for SPS-delivered power, and to establish a framework for comparisons of the various SPS systems architecture options defined by the IAA study.

Economically driven growth in the demand for energy will directly determine the greenhouse gas emissions and potential climate impacts that result. Moreover, there is the increasing likelihood – the timing of which is still uncertain – that the production of key fossil fuels will peak during the coming decades, resulting in further risks to the global economy and quality of life.

Each of the scenarios described this Chapter are intended to capture particular aspects of the future and to provide a context for laying out more detailed architectures and concepts-of-operations for future Solar Power Satellites. Specific architectures for SPS (e.g., lower cost, larger-scale RF systems versus high-cost, smaller-scale laser systems) may then be compared to one another in terms of their potential to meet the energy requirements of the several Scenarios. The characterizations of possible future energy costs presented here are not intended as literal quantitative forecasts; instead, they are formulated to suggest what sorts of SPS systems might be more or less profitable depending on the Scenario in question.

Based on these cases, the most dramatic increases in the cost of primary baseload power might be expected in the later term if available supplies of key fossil fuels begin to fall behind market demand earlier in this century than expected. However, strong "green energy" policies could lead to the most favorable nearer-term environment in such primary markets. These policies would result in higher prices in the nearer term, but avoid the market risks of either fossil fuel depletion earlier than hoped (Scenario Gamma) or significant climate change (Scenario Beta) in the mid-to-latter half of the century.

In all cases, niche markets that might pay higher prices than well-supplied commercial baseload markets represent attractive options. Remote and/or leveraged commercial markets appear particularly attractive in all cases, but especially in the case of Scenario Gamma ("Fossil Fuels Run Out") in which conventional fuels are depleted, but no special preparations are made early enough to offset the resulting energy price increases.

It is clear that solar power delivered from space could play a tremendously important role in meeting the global need for energy during the 21st century. There are four principal drivers for this conclusion. First, there is the very, very likely (but not certain) increase in global populations. Second, there is the projected dramatic increase in the worldwide per capita demand for energy to enable economic development. In addition, based on the consensus of scientists and numerous governments, there is an urgent and continuing need to develop huge new renewable energy sources to resolve the challenge of greenhouse gas emissions from fossil fuels, and the increasingly certain risk of global climate change. Finally there is the growing uncertainty in global supplies of existing fossil fuels; the issue of "peaking," which, if it occurs earlier rather than later and affects multiple fossil fuels, could lead to drastic increases in energy prices (thereby strangling economic development). Whether SSP can play a role in meeting the challenges depends in part on the cost of developing and deploying power from space as well as on the marketplace into which that power will be delivered.

One of the goals of the preceding discussion was to set the stage for Chapter 12, when we will return to the puzzle: depending on the future we face, what will be the terrestrial energy market environment into which Space Solar Power would be introduced? Before we turn our attention to that question, however, we have a lot of ground to cover. Let's begin with a discussion of the past forty-plus years, and the origins and history of the concept of Space Solar Power.

[2-1] Of course, there has been a remarkable increase in recent years in the supply, and resulting decrease in the price, of natural gas in North America. This has been due entirely to the emergence of a technique known as "hydraulic fracturing" (a.k.a., "fracking") and horizontal drilling which release so-called "tight" gas and oil from previously unproductive shale rock formations. The importance (and risks) of fracking will be discussed in greater detail in a few pages. However, even these newly available fossil fuels will not last indefinitely given the rapidly growing global demand for energy.

[2-2] Strickland, John K.; "Base Load Power From Earth and Space," (Presentation at "SPS 2009" Workshop; Toronto, Canada). 8-11 September 2009.

[2-3] Sources for the data in Table 2-1 are manifold; they include the International Energy Agency (IEA) 2010 Forecast, the U.S. Department of Energy (US DOE International Energy Outlook (DOE/EIA-0484) 2010), and others. Particular references include:

http://www.prb.org/Publications/PopulationBulletins/2001/WorldPopulationFuturesPDF338KB.aspx

http://www.eia.doe.gov/oiaf/ieo/

http://www.worldenergy.org/publications/survey_of_energy_resources_2007/solar/719.asp

http://www.iea.org/

http://www.worldenergyoutlook.org/

[2-4] The energy consumption projections shown are rough estimates only; they were developed for use by the IAA. They reflect a range of estimates from various organizations as well as considerable uncertainties – including various projections of "high, medium and low" economic growth scenarios and variations in the economic efficiency of the energy (i.e., kW-hours per unit of Gross Domestic Product (GDP), etc.).

[2-5] The projections of the percentage share of total energy from renewable energy technologies is uncertain, of course; however, it is directly related to the CO2 projections presented.

[2-6] References include:

http://rainforests.mongabay.com/09-carbon_emissions.htm

[2-7] Longer-term projections of CO_2 emissions should be regarded as more uncertain than the projections of global energy consumption on which they depend. The available projections vary based on assumptions about the economic efficiency of the energy use, the mix of energy sources, etc. Values shown for CO_2 emissions are approximations of the highest and the lowest projections presented in relevant IPCC studies.

[2-8] References include:

http://rainforests.mongabay.com/09-carbon_emissions.htm

http://co2now.org/

http://www.ipcc.ch/ipccreports/sres/emission/index.php?idp=116

[3-9] British Petroleum; BP Statistical Review of World Energy, (see: www.bp.com/statisticalreview). June 2012.

[2-10] The United States by itself consumes far more energy that the average across Western nations.

[2-11] The "logistic curve" is the technical name for the famous "S-Curve" that technology writers speak about; Reference: http://en.wikipedia.org/wiki/Hubbert_peak_theory

[2-12] In 1798, Malthus published his seminal monograph: *An Essay on the Principle of Population*; See: http://en.wikipedia.org/wiki/Thomas_Robert_Malthus

[2-13] There are any number of references on this topic; see for example:

http://www.businessinsider.com/fracking-shale-extraction-and-depletion-2013-3?op=1

http://www.forbes.com/sites/insead/2013/05/08/shale-oil-and-gas-the-contrarian-view/

http://en.wikipedia.org/wiki/Oil_depletion

The article in Forbes is quite good.

[2-14] The forecast in Figure 2-2 does not include the possible future harvesting of what are called "methane hydrates" from the ocean floor (on various continental shelves). Although technically possible, these hydrocarbons are prohibitively expensive to obtain based on currently known techniques (orders of magnitude

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more than even the least commercially-viable of other options). If methane hydrates become commercially viable in future, the consequences for climate change risks will be severe.

[2-15] Let me be clear on what this chart is / is not: Figure 2-2 does not indicate what I believe will happen. However, it does illustrate what might happen. The total area under the dashed "Annual Energy Consumption" curve represents roughly the total known and expected-to-be-found fossil fuel assets of Earth. This baseline simply assumes that, on the whole, demand for energy will drive burning all of the available fossil fuels just as fast as possible, until those fuels begin to be more and more expensive to extract and are eventually depleted.

[2-16] These tests, and the wonderful WPT research and development performed by Prof. Nobuyuki Kaya and his team from Kobe University in Japan, are explained more thoroughly in later in the text.

[2-17] For example, see: http://www.eia.gov/oiaf/1605/ggccebro/chapter1.html; and http://oncirculation.com/the-basics/climate-change/how-much-carbon-dioxide-have-we-emitted/.

[2-18] As of 2013, there continued to be significant controversy and debate regarding the reality of anthropogenic climate change, and concerning the uncertainty over the degree and the rate of climate changes that might occur due to growing CO_2 concentrations that have been measured over several decades. The approach taken by the IAA has been to consider these and other factors in terms of high-level global Scenarios that reflect alternative future outcomes that would materially affect the future energy marketplace; these are described in detail in Chapter 6 on Markets and Economics.

[2-19] See: Hoffert, M., et al, "Stability: Energy for a Greenhouse Planet Advanced Technology Paths to Global Climate," (*Science*, **298**, pp. 981-987), 1 November 2002. I was happy to be one of the several co-authors, with responsibility for the section on SSP. As I recall, it took some 18 months to get this paper through the peer review process; a rather long time for a paper that made what is now an obvious point.

[2-20] For the details of IPCC activities and results, see: www.ipcc.ch/

[2-21] Future integrated end-to-end systems studies of SPS should include rigorous examinations of the economic framework for SPS platforms. A scenario-based approach could provide the most comprehensive methodology for such studies.

[2-22] Please note that the specific price points for different energy sources delineated in Table 6-2 are **not intended** to be interpreted as a literal, quantitative forecast. Rather, they are presented strictly as suggestive of what might be expected as a result of the emergence the different alternative futures sketched in Table 2-2.

Chapter 3

Beginning at the Beginning: A Brief History of Space Solar Power

Where were we Then? Where are we Now?

> *"Those who cannot remember the past are condemned to repeat it…"1*
>
> *George Santayana (c. 1905)*

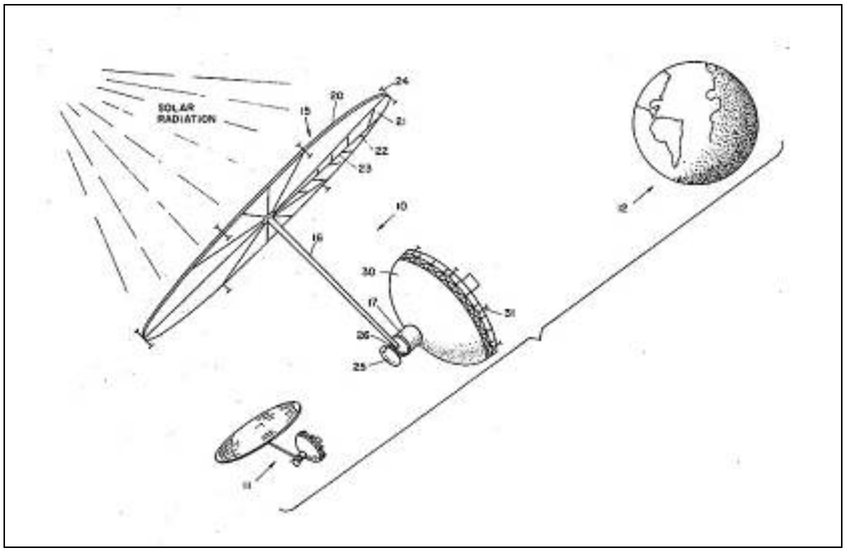
Précis

It has been said that making predictions is a tough business – particularly about the future.[2] It has also been said that those who fail to recall the mistakes of the past are doomed to repeat them. Both are certainly true for new energy technologies, and especially in the case of Space Solar Power. So, before attempting to see into the future, it makes sense to look to the past.

When Dr. Peter Glaser first conceived of the "Solar Power Satellite" (SPS) around 1965, the "space age" was less than ten years along. Glaser, who was at Arthur D Little, Inc. of Cambridge, Massachusetts at the time, had studied as an undergraduate in Prague (at that time in the former Czechoslovakia), and earned his Ph.D. in mechanical engineering from Columbia University in the US.[3] Figure 3-1 presents a conceptual illustration of an SPS from Dr. Glaser's original patent on the concept, filed in 1968 and granted 25 December 1973.

The SPS concept is really quite an elegant solution to the challenge of providing sustainable energy for humanity: a number of large platforms, positioned in space in a high Earth orbit where they can on a global scale collect and convert solar energy into electricity. This power is then used to drive wireless power transmission (WPT) systems that dispatch the harvested solar energy to receivers on Earth. With the right system concept, an SPS can be immune to nighttime, to weather, and to the changing of the seasons. A Solar Power Satellite positioned near geostationary Earth orbit (GEO) or beyond has the potential to deliver much more energy than ground-based solar power, to do so almost continuously, and to achieve much greater energy-efficiency than ground-based systems.

Figure 3-1 Illustration of the SPS Concept from the 1973 Peter Glaser Patent



Credit: US Patent and Trademark Office; Patent No. 5019768

Since its invention, there have been numerous studies and technology projects conducted by various government agencies, companies and universities that have been focused on the goal of the Solar Power Satellite. The first serious effort involved a series of studies conducted during the late 1970s in the United States by the Energy Research and Development Agency (ERDA) – the predecessor of the Department of Energy – working with the National Aeronautics and Space Administration (NASA). Figure 3-4 presents a high-level image of the principal systems architecture produced by this effort: the 1979 SPS Reference System. Unfortunately, in 1980 US government-sponsored SPS activities were terminated following unfavorable reviews by the Congressional Office of Technology Assessment (OTA) and the National Research Council (NRC)[4] based on the near-term feasibility of the systems concepts and related project implementation planning (including, in particular, the huge cost estimates).

On the positive side, the 1980s and early 1990s saw increasing international studies, technology R&D, and small-scale demonstration projects, particularly in Japan, but also in Europe and Canada. These efforts resulted in a number of important technical advances, discussed later in this report. Then, in 1995 under the auspices of a recently created Advanced Concepts Office in Washington, DC, NASA initiated its first systems studies of the concept of

SPS since the cancellation of efforts around 1980. This led to the “Fresh Look” study and a subsequent series of exploratory research and technology efforts. By 2000, it was generally agreed that the SPS was technically feasible. Moreover, although the necessary capabilities did not exist to assure the economic viability of SPS, still the research and development (R&D) path to developing these satellites was judged to be of great potential value to future space endeavors. This was the conclusion of the review of SPS studies in 1980, and the finding of an independent peer review conducted by the US National Academy of Sciences (NAS) National Research Council (published in 2000).

International interest in Space Solar Power (SSP) increased dramatically during the past decade – driven by the general concerns discussed previously and enabled by a wide range of impressive advances in key component and subsystem technologies. This interest has been expressed through a variety of R&D efforts, including studies and technology development in the U.S. (by both NASA during 1995-2003, and the National Science Foundation (NSF) during 2001-2003). Efforts have included ongoing R&D in Japan [e.g., by the Japanese Aerospace Exploration Agency (JAXA) and the Unmanned Space Experiments Free-flyer Institute (USEF)], recent and ongoing studies in Europe [e.g., by the European Space Agency (ESA)], more recent studies in the U.S. – including for the first time studies performed for the Department of Defense (DOD), as well as interest in other space-faring countries of importance, such as India and China.

The following discussion traces the almost 50 years of history of the SPS concept, highlighting the legacy of those years for the present and the future.[5]

Technological Foundations of Space Solar Power

When Peter Glaser conceived of the SPS, the Cold War was at full throttle and the era of rockets and satellites had only been underway for eight years or so. However, the technological foundations for Space Solar Power had already been established, and these transformational new capabilities informed his remarkable accomplishment. These five technology keystones included: (1) high-efficiency microwave emitters; (2) photovoltaic (PV) solar arrays; (3) solid state electronic diodes and the “Rectenna;” (4) large-scale Earth-to-orbit (ETO) transportation; and (5) Earth-orbiting spacecraft systems.

High-efficiency microwave emitters. Although extensive research on "radio detection and ranging" (RADAR) had been underway in the U.S. for some years by the time of the Tizard Mission[6], the arrival of the revolutionary cavity magnetron in mid-1940 sparked a transformation and rapid acceleration of U.S. efforts. Before the arrival of the fist-sized device in a plain back box, US planners had dismissed RADAR as a weapon for "the next war." After the cavity magnetron's arrival and demonstration of 1000-times the power output of the best competitor available (a much larger device known as a "Klystron"), the development of systems exploiting the new technology became a national priority virtually overnight. The magnetron demonstrated that microwaves could be generated at high power and high efficiency. These developments affected not only the course of World War II, but they also led to the immediate establishment of the "RadLab" ("Radiation Laboratory") in association with MIT, and the later emergence of Raytheon Corporation as a leading US company in electronics and microwave technologies.

Beginning with Dr. Glaser's original 1968 paper proposing the Solar Power Satellite, studies of the concept into the mid-1970s assumed that the larger and by then high-power Klystron tubes would be used for SPS WPT rather than magnetrons. It was not until the late 1970s, that Richard (Dick) Dickinson of the NASA Jet Propulsion Laboratory (JPL) suggested using magnetrons for SPS – a position that was supported by Raytheon Corporation and one of most important early leaders in the emerging field of WPT, Willam C. (Bill) Brown.[7] (We will return once again to the remarkable accomplishments of Brown and Dickinson in a moment.)

> At any event, when Glaser first conceived of the SPS circa 1965, one keystone technology that had been well established (and since the 1940s) was that of high-efficiency, high-power microwave emitters.[8]

Solid State Electronic Diodes and the Rectenna.

To make long-distance wireless power transmission (WPT) work here on Earth, three issues must be resolved: (1) Earth's atmosphere must be transparent at the wavelength of the electromagnetic (EM) energy to be used;[9] (2) the transmitter must produce EM energy at high power; and (3) the receiver must convert the EM energy back into electricity with high efficiency. Beginning in 1959, Bill Brown and other engineers at Raytheon Corporation undertook the challenge of power transmission at microwave wavelengths.[10] And, in 1961, Bill

Brown was the first to give a conference paper identifying the technology then available to accomplish Nicola Tesla's dream of WPT.

Following three years of intensive effort at Raytheon, in 1964 Brown and his team demonstrated microwave WPT from a transmitter on the ground to a flying, albeit tethered, helicopter in a project sponsored by the US Army. This accomplishment became widely known when it was publicized on Walter Cronkite's evening news TV program. This test was followed by years of focused studies, research, and development – and by growing interest in WPT (and SPS) by NASA and various companies, including Raytheon in Massachusetts, Grumman Corporation in New York, and others. In 1975, Brown (still at Raytheon) and Dick Dickinson of JPL succeeded in the highest power test of WPT ever accomplished: a 30-kilowatt transmission over a distance of about one mile. As shown in Figure 3-2, this test was performed at the Goldstone Deep Space Network (DSN) station in the California desert using one of the giant DSN dishes (designed for use in communicating with spacecraft in deep space) as the transmitter.

Figure 3-2 Photograph of the 1975 WPT Test at Goldstone, California

Credit: NASA (c. 1975)

The key innovation that made these accomplishments possible was the *Rectenna* (a.k.a. the "rectifying antenna"), which used simple electronic devices known as "diodes" to convert a microwave beam from RF energy back into electricity at remarkably high efficiency.[11] In 1965 when he invented the SPS, Glaser put this emerging keystone technology to use in the SPS concept. Together, these first two keystones – high-efficiency microwave emitters and receivers – enabled wireless power transmission, without which the concept of the SPS would have been impossible.

Large-scale Earth-to-orbit transportation.

Late in 1919, Robert A. Goddard presented a seminal paper entitled "A Method of Reaching Extreme Altitudes," in which he outlined his investigations of rocketry and with uncommon prescience suggested that a rocket might be sent to the Moon. Early the next year, on January

13, 1920, the prestigious New York Times ridiculed the shy scientist in a now-infamous editorial, saying Goddard

> "…does not know the relation of action to reaction, and of the need to have something better than a vacuum against which to react – to say that would be absurd. Of course he only seems to lack the knowledge ladled out daily in high schools."[12]

However, in less than four decades – by the mid-1950s – the idea of going into space had progressed from purely fantasy to a real engineering possibility that many, if not most Americans believed would be realized within a few years. By the mid-1960s – less than a decade later and driven by the shock of Sputnik – US Earth-to-orbit (ETO) space launch capability had gone from none at all to a routine (but still exciting) weekly occurrence. And by then it was just a few years before the first launch of the huge Saturn V booster as part of the Apollo program. Space launch had become a reality, with robots going as scouts to the Moon and beyond, and the US and USSR racing to send the first humans to the Moon.

In less than a decade, the technology had progressed from a booster capable of launching no more than a basketball-sized, battery powered satellite into a short-lived low Earth orbit, to monster boosters capable of launching more than 100 metric tons into space. Certainly, when Dr. Glaser assumed the keystone technology of ETO transportation for his SPS concept, no one doubted that launching large systems into space would become possible in the coming years.

Photovoltaic (PV) Solar Arrays.

There were some early uses of sunlight using heat engines and concentrators to do work beginning in the 19th century. However, it was not until the explanation of the photoelectric effect by Albert Einstein in 1905 and the subsequent development of photovoltaic solar cells that the later application of PV solar arrays in early spacecraft became practical.[13]

In the mid-nineteenth century, the photoelectric effect had been observed by various researchers, and as early as 1902 and 1908, solar-powered steam engines had been build and operated in St. Louis, Missouri and Needles, California. They provided up to 20 horsepower, equivalent to about 15 kilowatts. Despite this promising start, solar power was overshadowed for decades by advances in power generation provided by internal combustion engines. It was not until fifty years later, when advances in solid state physics made possible power generation based on the photovoltaic (PV) effect, that real progress began for solar energy.[14] In 1954, the first modern solar cell was developed at Bell Laboratories; fabricated in silicon, it delivered a net efficiency of six percent! And only four years later PV cells were deployed to power the Vangard satellite, the first use of solar energy in space. Progress came quickly, with improvements being sought concurrently in solar array efficiency, cost, and (for space applications) weight. Within the next half-dozen years, solar cells had been applied in diverse satellites.

At a result, in 1965, PV solar arrays (and their use in spacecraft) were well known, and Glaser also applied this keystone technology in creating the concept of the Solar Power Satellite.

Earth-orbit spacecraft systems.

Following the USSR's launch of the world's first artificial satellite in 1957 (Sputnik), the US responded with the development of a number of expendable launch vehicles as well as diverse Earth-orbiting and deep space satellites. Satellites developed by both countries included numerous long-lived – and therefore solar powered – commercial communications satellites (such as Echo, Telstar, and Intelsat), weather observing satellites (such as Tiros), and military satellites (such as Molniya from the USSR). Although tiny in comparison to the tremendous scale that would be required for an SPS platform, these early spacecraft nevertheless demonstrated the basic feasibility of automated spacecraft powered by solar energy and delivering RF transmissions to receivers on Earth. By 1965, spacecraft powered by solar arrays (as well as chemical and nuclear batteries) were well known, and Dr. Glaser could also apply this keystone technology to his invention of the Solar Power Satellite.

Based on these emerging keystone technologies, Glaser first broadly proposed the SPS concept in a seminal paper published in the journal *Science* in November 1968.[15]

1968: Power from the Sun

At the time of his paper in *Science*, Dr. Glaser was the head of the Engineering Sciences Department at Arthur D. Little, Inc. in Cambridge, Massachusetts, just down the road from the site of the famous "RadLab" of the 1940s. Inspired by the remarkable technology advances of the prior decade, Glaser formulated a transformational new concept: the SPS.

Glaser's paper articulated a compelling logic. First, he observed that the fossil fuels that provide the overwhelming majority of energy to enable industrial civilization will inevitably become depleted at some point during the next few hundred years (See Figure 2-1). He noted that it takes time – decades, if not longer – to mature and deploy a new energy technology after it has first been conceived. In Dr. Glaser’s view, the only scalable options that might replace fossil fuels when they “ran out” were nuclear power or solar energy. And, given the limitations of ground-based solar power on large scale, it is at this point in his argument that he introduced the new concept of Space Solar Power for the first time. In his paper, Glaser presented an overview of his notional architecture for an SPS, which is the earliest version of the concept that I have seen. This architecture – a sketch of which is presented in Figure 3-3 – is quite interesting.

Figure 3-3 Sketch of Peter Glaser's Original 1968 SPS Architecture[16]

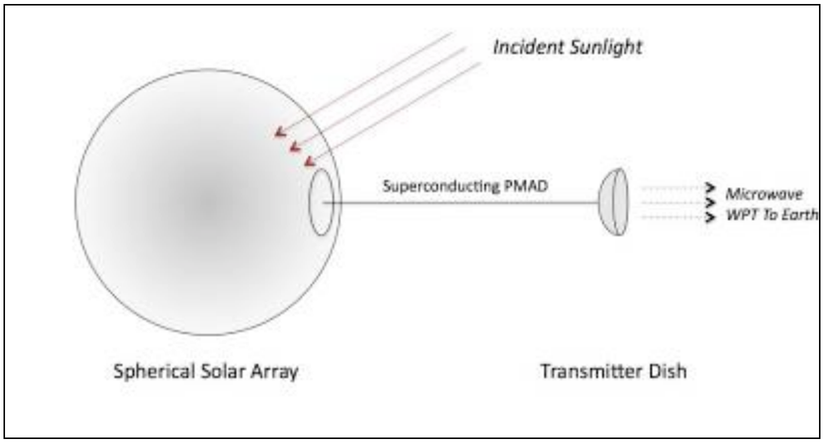


Image Credit: Artemis Innovation Management Solutions LLC (2013)

As shown, it comprises three principal elements: (1) a large dish transmitter, some 2,000 meters in diameter and powered by large, high power Klystron tubes; (2) a spherical PV solar array several thousands of meters in diameter (rather like a huge version of the inflatable *Echo*, NASA's first communications satellite, launched in 1960); (3) a superconducting power management and distribution (PMAD) system connecting those two; and, (4) supporting systems (such as attitude control, refrigeration systems, etc.).

The 1965 paper took a global view, looking at the energy needs of the world as well as the US. After stepping through potential global markets, key technologies and various important design factors, Dr. Glaser's seminal 1968 paper concluded with an admonition. "We should not," he observes, "underestimate the development efforts that will be required to construct, launch, and operate the suggested solar-power-generating satellite." However, he observed – as was confirmed by the US National Research Council in 1980 and again in 2000, and by the International Academy of Astronautics in 2001 – that SPS do not require the discovery or development of new physical principles.

The remainder of this Chapter retraces the story of the Solar Power Satellite over the past 40-plus years, highlighting the institutions, programs and people that have created, championed, and developed this elegant, but little known, idea.

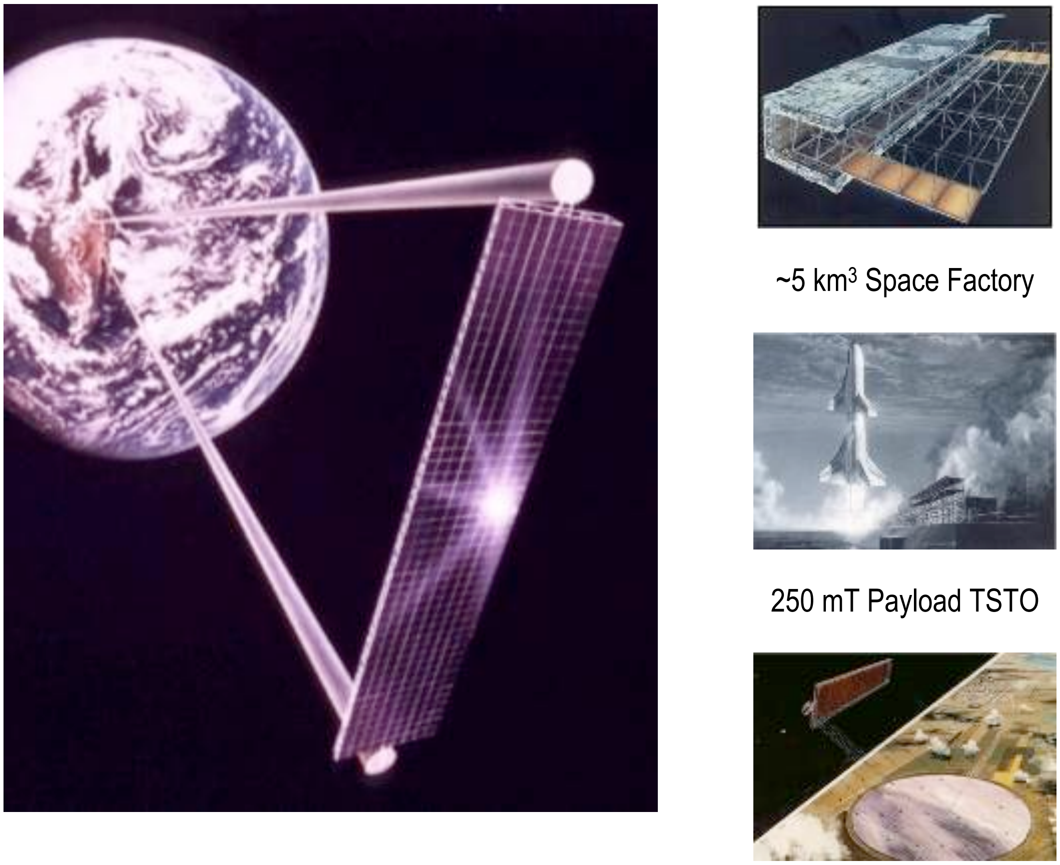
1970s: Early Years for the Solar Power Satellite

Following Peter Glaser's initial proposal of the SPS concept in 1968 and the cancellation of NASA's Apollo program a few years after the first lunar landing in July 1969, both industry groups and NASA became interested in the new concept. The then-emerging Space Shuttle program emphasized frequent launches for the reusable ETO vehicle, where those projections were justified by ambitious space goals: space settlement and/or the commercial development of space (e.g., SSP) would be required.

This early interest in the SPS concept resulted in intensive studies conducted by U.S. industry and government organizations by the mid-to-late 1970s. In 1976-1977, the then-Energy Research and Development Agency (ERDA) – which was later renamed the Department of Energy (DOE) – initiated a several year study program in cooperation with NASA, intended to evaluate the potential of SPS and provided recommendations as to whether they should become a serious option for the future. Figure 3-4 is an illustration of what was known as the "1979 SPS Reference System" from that era. (Details of this and other concepts are discussed in Chapter 4.)

Supported by NASA, the DOE's Concept Development and Evaluation Program (CDEP) effort was funded at a level of approximately $90M ($, FY2013, or about $20M in 1978 dollars). However, the emphasis in those studies was on implementation of SPS systems, not the framing of strategic R&D goals or initial demonstrations. Unfortunately, the most detailed SPS architectures were technically complex and unlikely to be economically viable.

Figure 3-4 Illustrations of the 1979 SPS Reference System Concept



~5 km^3 Space Factory

250 mT Payload TSTO

1979 SPS Reference System (10 GW Version)

Ground Receiver

Image Credit: NASA-DOE Sponsored Graphics

As illustrated in the left panel of the figure, the SPS platform was huge (involving live solar arrays about 5,000 meters by 25,000 meters in area), the transmitters were enormously heavy (driven by large high-power Klystron RF tubes), and the power management and distribution (PMAD) system was huge and very high voltage (with power levels of more than 14,000 MW on-board and more than 10,000 volts). Similarly, the baseline concept called for enormous platforms to be constructed in space; as illustrated in the upper right, with dimensions of roughly 01 km by 0.5 km by more than 5 km, to construct the SPS platform). Space launch was equally large and ambitious, calling for fully reusable systems – as shown in the middle right panel of Figure 3-3 – that were about 5-times larger than the US Space Shuttle (which had not yet flown in 1979). And finally, as shown in the lower right panel, the ground receiver (comprising millions of Rectennas) was envisioned to be as much as 10-12 km (i.e., about 6 miles or more) in diameter. The results of these studies were very well documented, with detailed reports encompassing some dozens of volumes.

In fact, there was not a single SPS concept. Rather, there was a family of related concepts, each representing variations – some relatively modest – on the Reference System. Taken all together, the better-defined SPS approaches of the latter 1970s suffered from a number of significant technical and programmatic challenges, including:

(1) Low technology maturity;

(2) Excessive weight, due in part to huge, high-voltage power management and distribution (PMAD) carrying up to 7,000 MW at more than 10,000 volts across a rotating gimbaled interface;

(3) Projected development costs for a monolithic platform more than 20 times larger than the International Space Station;

(4) The up-front expense of the required fleet of heavy-lift reusable launch vehicles (RLVs); for example two-stage-orbit (TSTO) vehicles with payload requirements of up to 250 mT; and,

(5) The need for hundreds of astronauts and thousands of robots for SPS construction operating in large space factories at various orbits, and potentially of enormous scale.

All told, the program to develop this SPS platform approach, the supporting infrastructure, and some 60 platforms was estimated to require more than 20 years and to cost more than $1,000-to-$3,000 billions (in then-year dollars). Reviews by the Congressional Office of Technology Assessment (OTA) and the National Research Council (NRC) resulted in highly negative findings – not surprisingly.

SPS advocates viewed the study conducted by ERDA (and later DOE) and NASA not with enthusiasm but rather with considerable skepticism, and with some reason. As noted by Phillip K. Chapman in a 1981 article in the space advocacy newsletter, L5 News,

> "At the time, many space advocates believed the CDEP was an attempt to delay if not kill the SPS, and there is no doubt that DOE management was and is hostile to the concept."[17]

However, Chapman continued, the leaders of the CDEP were not at fault,

> "In practice, … the DOE and NASA staff undertook a serious and honest study of the system and its ramifications. They deserve to be commended: the CDEP could serve as a model for careful technology assessment."

As mentioned above, the DOE-NASA SPS Concept Development and Evaluation Program is best remembered for the "1979 SPS Reference System," which used a NASA-developed Reference System configuration as the basis for environmental, societal, and comparative economic assessments.[18] The central feature of this concept was the requirement for a stupendously large-scale power infrastructure in space, consisting of about 60 SPS, each delivering 5 gigawatts (GW) of base load power to the U.S. national electrical grid (for a total delivered power of about 300 GW). However, connections to interim applications of Space Solar Power were tenuous and the space infrastructure requirements were projected to be significant. In addition, the "cost-to-first-power" of the 1979 Reference System was expected to be more than $350 billion (in 2013 dollars).

A number of enduring champions and subject matter experts came into the field of Space Solar Power in the 1970s. Mr. Richard Dickinson of NASA's JPL was mentioned previously in connection with his work in the field of WPT, as was Mr. William C. Brown of Raytheon Corporation. Others included Mr. Hubert (Hu) Davis, who served as Chief of the Transportation System Office at the NASA Johnson Space Center (JSC) in the 1970s and remains today an advocate of SPS,[19] and G. Dickey Arndt, an expert in the field of microwave WPT R&D at the NASA Johnson Space Center (JSC) in Houston, Texas. Others included Ralph Nansen, an Apollo Program launcher engineer and designer in the 1960s who managed The Boeing Company's SPS efforts from 1975 until 1980; he remains a spokesperson for SSP to this day.[20] Gordon Woodcock, also at Boeing and later at the NASA Marshall Space Flight Center (MSFC), also led various important SPS studies in the 1970s. Yet another early SPS leader was Owen E. Maynard, a Canadian who became a leader during Apollo in the design of the Lunar Excursion Module (LEM), and upon leaving NASA joined Raytheon Company in Massachusetts. Working with another Raytheon engineer – William (Bill) Brown – Maynard supported various SPS and WPT studies. Ultimately, around 1978-1980 Maynard took a strong interest in a novel design concept known as the "sandwich module" approach to wireless power using solid-state devices to generate the microwave power.[21] (This architecture became the basis of the later work of

Japan's leading WPT expert, Prof. Nobuyuki Kaya, and was a key starting point in the new SPS-ALPHA concept; both are discussed in the next Chapter.)

Another champion of SPS whom I must mention emerged from the formal study efforts of the 1970s: Fred Koomanoff, the manager of ERDA's and then DOE's SPS program from its start until its end. Koomanoff was a strong proponent of the enormous amount of technical work done during the SPS Concept Development and Evaluation Program (CDEP), and always regretted and resented what he regarded as the unfair characterization of the CDEP as little more than the 1970 SPS Reference System. Two of Koomanoff's younger team members were Leonard David, who has been for many years a well-regarded space journalist, and Alan Ladwig, who became NASA Associate Administrator for Policy and Planning in the 1990s. Both are still well known in space circles.

Throughout the studies of the 1970s, Earth-to-orbit (ETO) transportation was identified again and again as an enduring problem for the economic viability of the concept of SSP. Around 1980-1981 – just at the end of the first round of US SPS activities – Prof. David Criswell of the University of Houston conceived a radically different approach: Lunar surface based Solar Power (LSP), which avoided the entire space transportation issue by building SPS system elements on the Moon's surface from lunar materials. Prof. Criswell spoke on the LSP concept, which he patented, many times during the next 30-plus years.

Probably the most famous and influential of SPS – and space development – advocates from the 1970s was Dr. Gerard K. O'Neill of the Space Studies Institute (SSI), at Princeton University in New Jersey. Famously, O'Neill suggested the idea of large, artificial gravity space habitats in the mid-1970s, and in 1975 the construction of GEO-based SPS from lunar materials.[22] SSP and the concepts of space development and settlement were potent visions some thirty years ago, and remain so today. O'Neill's efforts inspired others outside of the government programs and the aerospace firms who became champions of SPS and the use of space resources. One was former Chicago lawyer, and later Vice President and then President of the SSI, Gregg Maryniak. Another was Marylander Paul Werbos who later joined the US National Science Foundation (NSF).

The 1980s: After Formal US Government Efforts Stopped

Even though national-level U.S. activities to development Solar Power Satellites were terminated following the negative reviews in 1980, international interest (and research and development) continued addressing the goal of Space Solar Power.

International Activities – General

Throughout the 1980s (and into the early 1990s), interest and activities concerning SPS continued in several countries, including Japan, France and Canada, and internationally, particularly through the International Astronautical Federation (IAF) Power Committee and the SunSat Energy Council (a non-governmental organization (NGO) founded by Peter Glaser in the late 1970s). As various component technologies advanced, novel SPS systems approaches were invented and by the mid-to-late 1990s, work in the US had resumed and by the end of the decade it was broadly agreed that the SPS concept was technically feasible. Nevertheless, doubts remained that sufficient capability did not exist for the concept to achieve economic viability.

Several of the international champions of the SPS concept who emerged during this decade merit recognition. Their activities spanned several continents, countries and the decade.

France

Guy Pignolet of the French Space Agency (CNES), for example, became an ardent advocate of SPS and participated for many years in the annual IAF symposium and periodic SPS and WPT focused international conferences. Another French champion for SPS and other future energy options is M. Lucien Deschamps of EDF (Electricite de France SA), as well as a forward-looking non-governmental organization, *Prospective 2100*. Two key SPS events took place in France during this timeframe: in 1986, the first international SPS symposium (SPS'86), and in 1991, the second (SPS'91). These meetings laid the groundwork for the series that continues to the present and provided a framework for creation of an international community of interest around SSP that supported the creation of the IAF Power Committee (discussed below).

Canada

A champion from Canada who followed in the footsteps of Owen Maynard was Bryan Erb, now retired from the Canadian Space Agency (CSA). Erb represented CSA for many years at the

NASA Johnson Space Center in Houston, Texas. For example, one of the noteworthy international SSP-related activities in Canada was 1987's "SHARP" (Stationary High-Altitude Relay Platform), a small-scale demonstration of wireless power transmission to an aircraft in flight.

Activities in Japan

Various organizations and individuals working in Japan made some of the most significant technical progress toward the goal of SSP during the latter 1980s (and into the 1990s and the years following). The key organizations included both government agencies and universities. There were several individuals who made the greatest contributions. One of those was Professor Hiroshi Matsumoto, former researcher and now President of Kyoto University, who organized research and ground breaking experiments in WPT. In the past decade, Matsumoto promoted the inclusion of Space Solar Power in Japan's Basic Space Law. Another was Masahiro Mori, formerly with JAXA (the Japan Aerospace Exploration Agency), where he pursued various SSP systems approaches, including laser WPT concepts. Professor Susumu Sasaki, recently retired from ISAS (the Institute of Space and Astronautical Science, formerly independent, but not a part of JAXA), was the lead for SPS studies at ISAS for many years. And, of course, Professor Nobuyuki Kaya, who was originally at the University of Kyoto with Professor Matsumoto and, during the past 20 years, has been leading his own team in ground-breaking WPT and SPS research at Kobe University.

In 1983, Professor Matsumoto's team at Kyoto University successfully conducted the MINIX (Microwave Ionosphere Nonlinear Interaction eXperiment) sounding rocket experiment using two separated payloads of a single sounding rock launch vehicle as microwave transmitter and receiver to measure the effects of WPT-type microwave transmissions on Earth's ionosphere. Kyoto University conducted a follow-on experiment in 1993: the ISY-METS (International Space Year - Microwave Energy Transmission in Space), which was also a sounding rocket experiment.

Other International Activities

International Astronautical Federation. One of the most important international accomplishments of the 1980s involved many of the individuals cited above; this was the establishment under the International Astronautical Federation (IAF) of a Power Committee (c. 1990), which began organizing one or more technical sessions on SPS at the annual International Astronautical Congress (IAC). More than 20 years later, these sessions continue to occur each year at the IAC and represent the longest recurring international forum on Space Solar Power.

International Space University. In addition to the IAF Power Committee, another important ongoing activity that relates (albeit to a lesser extent) to SSP is the "International Space University" (ISU). ISU was founded in 1987 by both Americans and others as a not-for-profit interdisciplinary post-graduate educational institution, dedicated to the development of outer space for peaceful purposes through international and multidisciplinary education and research programs (ISU Bylaws, Article 2.1). In addition to its unique annual summer Space Studies Program, ISU offers several degrees, including a Master of Science in Space Studies (MSS), a Master of Science in Space Management (MSM), and an Executive Master of Business Administration (EMBA). The Space Studies Program, ISU's Flagship, is a annual summer professional development program that has convened at various locations around the world since 1988.[23]

From time to time, the ISU summer program – which includes a focused technical project at every session – has touched on the topic of Space Solar Power. For example, in the summer of 1992, the fifth annual ISU summer session was held in the city of Kitakyushu, Japan; the session's technical program focused on the topic of Space Solar Power. Gregg Maryniak, by then Director of the Space Studies Institute, served as director for the SSP Design Project, which included some 97 students from 22 countries;[24] the goals of which, among others were to:

> "…produce an overall development program plan for the demonstration, testing and early commercial development of space beamed power systems up to and including initial space to ground tests…"

As noted, the emphasis was on a potential development program rather than novel SPS systems concepts. The report from this summer session, which makes good reading, was touchingly dedicated to the memory of Dr. Gerard K. O'Neill, who died before the session and had served on the board of Advisors of the ISU since its founding.

What about the US?

It really seemed that once the *program* for SPS was terminated in 1980-81, the *vision* of Space Solar Power became a "third rail" in space policy (i.e., it could not be mentioned) for official NASA (and the aerospace industry). At least SSP could not be mentioned by anyone who intended to be taken seriously in the US aerospace community. Some five years following the termination of the joint DOE-NASA SPS program in 1986-1987, there was a major review by the National Research Council (NRC) of NASA's space technology investments.[25] This review looked at a broad range of potential future space mission applications, including science missions beyond our solar system, a wide range of defense-related missions, commercial missions, and human space flight from the space station to a colony on the Moon and a human outpost on Mars. What the NRC's assessment did not consider was Space Solar Power. Under the category of "space power" technology, the report (and presumably NASA's briefing to the review panel) addressed no solar power technology needs beyond the year 2000. Only space *nuclear* power was discussed for the post-2000 era, or for applications larger than 50 kilowatts. In the 1980s, discussing ambitious future applications of Space Solar Power was almost, but not quite, taboo at NASA.[26]

Even though all policy-focused US efforts to pursue SPS ended in 1980-81, some activities did continue. For example, two universities won grants under NASA's Centers for the Commercial Development of Space (CCDS) program, the NASA Headquarters Office of Commercial Space (aka, "Code C") at that time.

One of these was located at Texas A&M University (TAMU). TAMU is a coeducational public research university located in College Station, Texas. It is the flagship institution of the Texas A&M University System. The seventh-largest university in the US, TAMU enrolls over 48,000 students in ten academic colleges. Texas A&M's designation as a land, sea, and space grant institution reflects a broad range of research with ongoing projects funded by agencies such as the National Aeronautics and Space Administration (NASA), the National Institutes of Health (NIH), the National Science Foundation (NSF), and the Office of Naval Research (ONR). The school ranks in the top 20 American research institutes in terms of funding and has made notable contributions to such fields as animal cloning.

With regard to SSP technology R&D, a key entity within TAMU was the Center for Space Power (CSP). CSP had a mission to work with industry to develop technologies for NASA mission needs and space power-related commercial ventures. The CSP developed a variety of space power-related technologies that were applicable to both space and terrestrial commercial activities, including specialized heat pipes, advanced battery components, novel electronic materials, digital communications algorithms, power conditioners, and a host of other power-related devices.

The CSP pursued the development of solar power from space as a non-conventional energy source for terrestrial application. In particular, the Center fostered development of WPT by either microwaves or lasers as an enabling technology for the importation of energy from space. (TAMU and CSP played an important contributing role in the performance of a WPT demonstration in 2008, described later).

In addition, even though formal US government efforts to study or develop SSP were terminated in 1981, from time to time activities that involved the SPS concept arose in the US. For example, in 1985 the Space Studies Institute (SSI) based in Princeton, New Jersey sponsored a study on the topic of SPS constructed from lunar materials.[27] As previously mentioned, SSI was the organization founded by Dr. Gerard K. O'Neil; O'Neill was quite well known in the 1970s because of his writings about, and advocacy of, large space habitats (based on the promise of very low cost access to space). The 1985 study pursued the idea that SPS could be manufactured largely from lunar surface materials, thus eliminating the cost of space transportation from Earth to geostationary Earth orbit.

In the mid-1980s, Congress and the President established the "National Commission on Space" (NCOS), chaired by former acting NASA Administrator Thomas Paine. With remarkably bad luck from a policy standpoint, the report of the Paine's National Commission was published in 1986 – at virtually the same time as the Challenger Space Shuttle tragedy. The NCOS dedicated an entire chapter to the topic of "Space Enterprise" (referring to the future commercial development of space). The report described the ideal space enterprise:[28]

> "The ideal space enterprise would have a stable, predictable, very large market on Earth, a potential for export sales, and once established, would not be dependent on Earth-to-orbit transportation costs to generate continuing revenues."

The report also noted that the commercial communications satellite industry satisfied all of these criteria except the first: it is limited to only a few billions of dollars per year – a small scale in the U.S. economy. However, the report did identify a prospective future space enterprise that could satisfy all of these criteria: Solar Power Satellites. As the report said:

> "One highly speculative space enterprise would, if technically and economically feasible satisfy all of the ideal conditions, including large market size. This enterprise would provide electric energy for Earth from satellites intercepting solar energy in geostationary orbit."[29]

Notice the use of the phrase "highly speculative." This choice of words gives a pretty clear indication of how far from favor SPS had fallen by the mid-1980s. Also, this was during the heat of the Cold War, an era when the popular President Ronald Reagan characterized the Union of Soviet Socialist Republics (USSR) as an "evil empire." The Commission argued that pursuit of SPS could be a new arena for international competition—not cooperation:

> "There would, of course, be competition; the largest conference so far held on solar power satellites was held in Japan. The Soviet Union has announced the goal of building the first solar power satellite to supply energy to Earth in the 1990s."

And the Commission believed that this was a race that the U.S. could win:

> "We feel that the United States would have sufficient technological skills and leadership to be able to dominate such a market if it develops, provided that U.S. research efforts continue."[30]

Of course those research efforts did not continue. And, unfortunately, in their final report the Commission made no recommendation concerning SPS. There were perhaps two principal reasons. First, by this time SPS was almost "taboo" as a topic; more on this in a moment. Second, because of the devastating tragedy of Challenger, the focus for years to come would be on the future of human (and to a lesser extent robotic) space exploration.

Following the SSI-sponsored study and the NCOS report (and in the context of planning for future human exploration missions that came before July 20, 1989) NASA chartered a study on the topic of possible lunar contributions to Earth's energy needs.[31] The study treated three options for lunar energy more or less equally: (1) SPS constructed from lunar materials; (2) lunar solar power (LSP), which is to say the construction of an SPS on the Moon's surface (discussed in Chapter 4); and, (3) high energy fusion using He^3 (i.e., a specific isotope of Helium known as "Helium-three") mined on the Moon and shipped to Earth. This study, although interesting, had no evident influence on the Space Exploration Initiative (SEI) that followed President George

H.W. Bush's speech at the Air & Space Museum.[32] U.S. R&D focusing on Space Solar Power did not reemerge until the 1995-1997 Fresh Look Study.

The 1990s: Progress and Renewal

The decade of the 1990s saw important areas of technical progress for the key technologies needed to realize SPS as well as a renewal of activities and interest in the US and NASA. Although still highly contentious, the 1990s also saw the emergence of a growing scientific consensus that climate change was occurring and that it was anthropogenic (i.e., caused by human activities), and due in large measure to the ongoing accumulation in Earth's atmosphere of so-called "greenhouse gases" (GHG) such as carbon dioxide. At the same time, the economies of both China and India remained relatively under-developed and the global price for energy reasonable – as reflected in the price for a barrel of oil at the end of the decade at about $15 per barrel.

In the US, the decade of the '90s began with a remarkable irony. Toward the end of the SEI (mentioned above) and the Bush Presidency, the US Department of Energy (DOE) examined a variety of technologies that might become areas in which the DOE laboratories could contribute to the Initiative. One of the several technology reports delivered from DOE to NASA (and the White House) concerned the topic of extraterrestrial resources.[33] Of these resources, the item mentioned first and foremost was the potential of "space energy resources" that might be employed to mitigate the "growing environmental cost" of energy, as well as "conflicts over control and use of Earth's resources." Meanwhile, international progress toward the realization of SSP continued.

International / Non-US Government Activities

There were several important international conferences addressing the topics of SPS and wireless power during the 1990s. First, in 1991, SPS'91 – the second international symposium on SPS was held in Paris, France. (This followed the lead of the first such meeting five years earlier, which was also held in Paris: SPS'86.) And, two years later in San Antonio, Texas the first technical specialist conference on wireless power was held: WPT'93. This event was followed in 1995 with another WPT workshop in Kobe, Japan (described below). Then, in 1997, Bryan Erb took the lead in organizing the third SPS symposium (SPS'97) in Montreal Canada.

Altogether, the early 1990s were a time of frequent meetings and considerable international government and non-governmental SSP and WPT research in the US and outside the US.

In addition to the various workshops and studies, and the Japanese sounding rocket experiments described above, another important highlight of international SSP activities in the 1990s was the formulation of the "SPS2000" concept in Japan when a group of researchers at Japan's Institute of Space and Astronautical Science (ISAS) conducted a feasibility study of a demonstration-scale Solar Power Satellite named "SPS2000, devised as a straw man mission to clarify the problem areas and for educational purpose. This platform was to have been built in an equatorial LEO orbit to reduce mission cost, and increase the amount of time the platform would spend over receiving stations located on the equator. It incorporated some 10MW of delivered electricity that would be received by ground stations located near equatorial nations that are mostly located in developing countries. (See Chapter 4 for a conceptual illustration of the unique SPS2000 concept.) Another champion of SSP, and in fact a unique researcher in the field, Dr. Patrick Collins supported the SPS-2000 efforts, and has worked as an educator at Azuba University in Japan for many years. Collins has spoken internationally many times on the SPS 2000 concept in particular, and SSP and terrestrial markets in general.

NASA and the US: Space Solar Power Comes Back… for a While

During 1995, after a hiatus of some fifteen years, NASA came back once more to the topic of Space Solar Power. As part of one of a series of reorganizations of NASA Headquarters during the 1990s, in late 1994 the Office of Space Access and Technology was formed, including the Advanced Concepts Office headed by long-time space innovator Ivan Bekey. Bekey tasked one of the members of his new office – this author – to reexamine the topic of Space Solar Power. The goal of this advanced concepts study was to determine whether new concepts – made possible by new technologies that may have emerged since 1980 – might make SPS/SSP more feasible. Happily, in 1995, Professor Nobuyuki Kaya of Kobe University in Japan organized "WPT 1995," one in a series of major international technical workshops on the topic of wireless power transmission. During the meeting, Prof. Kaya and his team conducted an ambitious demonstration of WPT from a ground transmitter (at about 5 kilowatts power) to a planar rectenna array on the underside of a lighter-than-air airship. (This was my first introduction to the international SSP community, and the beginning of a continuing friendship with Nobuyuki Kaya.)

The final report from what became known as the "Fresh Look Study of Space Solar Power," written by lead author Dr. Harvey Feingold and a team of co-authors, was published in 1997 by SAIC and is one of the most comprehensive, and more recent treatments of the topic. A central feature of the study and the report was an exhaustive effort to evaluate a wide range of possible new SSP / SPS system concepts, including both existing concepts and novel approaches. Ultimately, more than thirty distinct SPS systems were documented and roughly one-third of these were evaluated at varying levels of detail. From the *Fresh Look Study of Space Solar Power*, various approaches emerged for SSP that appeared to be much more viable – both technically and economically – than past systems designs.

During summer 1997, the NASA Administrator, Daniel Goldin, became interested in the topic of Space Solar Power (and at his request I prepared and made two different presentations to him in the June-July timeframe). As a result of these discussions, in early October (at the end of the *Fresh Look Study of Space Solar Power*, I was asked to make a briefing to NASA's senior management. The meeting was chaired by retired General Jack Dailey, then NASA Deputy Associate Administrator, with participation by Mal Peterson, NASA's Comptroller at that time, and a range of other senior officials from the several NASA Headquarters program organizations and NASA field centers. At the end of a two-hour briefing during which I presented the results of the Fresh Look Study, Peterson opened the discussion that followed by commenting to the group, "*every* new NASA program should have this level of preparation." Unfortunately, the conversation that followed this initial very positive feedback did not follow suit: at the end of numerous negative comments by a few participants, and nothing from the others, Gen. Dailey summarized the meeting by asking rhetorically: "is there anyone in the room – other than John – who thinks we should pursue this?" The answer was only silence.

Why had Space Solar Power been rejected by NASA's leadership? In my view, there were three factors. First and most important, the legacy of the 1970s – for years, SPS had been a taboo subject, a career killer; it was unlikely that even a neutral party would take such a chance. Secondly, there was strong institutional interest in pursuing a new space nuclear power (SNP) program: *SP-100* (the SNP program of the 1980s) had recently been cancelled and *Prometheus* (the space nuclear power created around 2000) had not yet been established. If large SSP systems were advocated, it might undercut winning an investment in space nuclear power. And, finally, NASA's goals were well established – science, human space flight, aeronautics – and budgets were finite. None of the organizations that represented those goals wished to see a new goal added to the mix.

Despite the negative reaction within NASA, the response outside NASA was quite positive. Because of the *Fresh Look Study of Space Solar Power* the US Congress (Space and Aeronautics Subcommittee of the House Science Committee), and the White House Office of Management and Budget (OMB) separately expressed interest in Space Solar Power during the winter of 1997-1998. The result was money added to NASA's budget: a suggested follow-on effort (conducted during Fiscal Year 1998), and the creation of the SSP Exploratory Research and Technology (SERT) Program. From FY 1999 through the end of FY 2000, with a total budget of about $22 million (then-year dollars) NASA implemented the SERT program, including systems studies, technology research tasks, and selected technology demonstrations.

Ultimately, many of the issues identified in 1980 – particularly regarding technical feasibility – were addressed by NASA's SSP studies and research and development (R&D) from 1995-2001, including the Fresh Look Study (1995-1997) and the SSP Exploratory Research and Technology (SERT) Program (1998-2001). Still, economic uncertainties remained, including:

(1) Insufficient efficiency of key devices (e.g., amplifiers, photovoltaic (PV) cells, etc.);

(2) The need for large-scale integration of key systems (e.g., PMAD, thermal management, etc.);

(3) Inadequate capabilities in space robotics and autonomy;

(4) The continuing need for RLVs prior to launching an initial SPS; and

(5) The lengthy R&D program required for an initial SPS pilot plant (estimated at some 20-25 years or more).

Another key product of the SERT program was a new integrated roadmap for the development of SSP – including technology developments and demonstrations, space applications of various interim system demonstrations, and leading to large Space Solar Power systems for use in space and the eventual delivery of power to Earth. This 2000 roadmap (discussed at greater length in Chapter 15) formed the basis for the next major milestone in the history of SSP in the US: a return to the National Research Council.

The Early 2000s: Increased Needs, Mixed Efforts

International interest in Space Solar Power increased once again during the years following 2000 – driven in large measure by (1) increasing concerns regarding climate change driven by greenhouse gas (GHG) emissions, (2) increasing international demand for conventional fossil fuels such as petroleum (driven by global economic growth), and (3) concerns regarding the possible market effects of early signs of the eventual depletion of those fossil fuels. A wide variety of impressive advances in key component and subsystem technologies also make this new interest in SPS possible. The decade opened with the concluding stages of NASA's renewed SSP activities from the late 1990s.

2000-2001. After NASA's SSP Fresh Look and SERT Activities

The NRC Review. Near the conclusion of the SERT Program, NASA contracted with the US National Research Council (NRC) Aeronautics and Space Engineering Board (ASEB) to conduct an independent evaluation of the SSP roadmap that had been developed by the program. The US National Academy of Sciences (NAS), through its National Research Council (NRC), has lead responsibility for evaluating (when requested) major US government science and technology policy options and decisions as well resulting program activities. During 1999-2000, the NRC conducted a major review of NASA's Space Solar Power R&D activities (e.g., the SERT program), and published its findings in a formal report (which is still available on-line).[34]

The goals of the NRC review included (1) critiquing the overall technology investment strategy in terms of the plan's likely effectiveness in meeting the program's technical and economic objectives; (2) Identifying areas of highest technology investment necessary to create a competitive space-based electric power system; (3) identifying opportunities for increased synergy with other research and technology efforts; (4) providing an independent assessment of the adequacy of available resources for achieving the plan's technology milestones, and (5) recommending changes in the technology investment strategy.

The efforts of the NRC's review of NASA's SSP roadmap resulted in a number of key findings, including the following: (a) NASA's "SERT program has provided a credible plan for making progress toward the goal of providing space solar power for commercially competitive terrestrial electric power despite rather large technical and economic challenges; (b) "Current SSP technology is aimed at technical areas with important commercial, civil, and military application; (c) the “NASA team has defined a potentially valuable future program; (d) “significant technical breakthroughs necessary to achieve final goal of cost-competitive terrestrial baseload power; (e) the “ultimate success of terrestrial power application critically depends on dramatic reductions in cost of transportation from Earth to GEO; and (f) “leveraging of technological advances made by organizations external to NASA must be done.”

All told, these findings – based on the new roadmap for Space Solar Power – were a far cry from the extremely negative findings vis-à-vis NASA’s plans for SPS development presented in the NRC review of 1980-1981. In the event there are future SSP activities sponsored by the US government, or in which US government agencies play a partnership role with industry, it is likely that the NRC will once again be involved in conducting either relevant or targeted peer reviews of the activity.

2001 - An International Forum on Space Solar Power

Just past the end of the decade of the 1990s, during the NRC review of the SERT Program and of NASA’s SSP roadmap, a remarkable meeting was organized at NASA Headquarters, with the support of the Office of Space Flight (OSF): *An International Forum on Space Solar Power*, 12 January 2001. (Around 1997, the former Office of Advanced Concepts to which I had been assigned when the Fresh Look Study was started and the Office of Space Access and Technology (OSAT) in which it resided were both dissolved in a sweeping reorganization of NASA technology investment management by Dan Goldin. I was reassigned to the Advanced Projects organization in the Office of Space Flight, where I remained until NASA was once again reorganized following the Space Shuttle Columbia accident.) The meeting, which was the first of its kind, comprised two major parts: a review in the morning of recent US SSP activities and future directions, and a series of presentations in the afternoon of international SSP activities and plans. The day began at 8 am with opening remarks by Mr. William (Reads) Readdy, Associate Administrator for OSF; it ended at 5 pm with a presentation on overall future directions for SSP by myself in cooperation with two close friends: Joseph T. Howell, manager of SERT program activities at NASA MSFC, and Dr. Neville I. Marzwell, manager of SERT efforts at NASA JPL. This Forum was the first time that representatives from several US and international space organizations met in a government-sponsored venue to discuss their respective plans for Space Solar Power.

SSP, NASA and the National Science Foundation

Despite the progress that had been made during the SERT Program and the positive outcome of the NRC review, NASA's interest in pursuing SPS-related R&D continued at the level of "little to nonexistent," and the Agency successfully dissuaded the White House (now occupied by President George W. Bush) from continuing to support those efforts. Toward the end of NASA's congressionally supported SSP activities (during 2001), a transition was needed, and the Agency undertook a joint competitive technology research solicitation with the National Science Foundation (NSF) and the Electric Power Research Institute (EPRI). The joint NASA-NSF-EPRI program, which comprised a range of technologies, was organized by myself at NASA Headquarters and by Paul Werbos at NSF (who had been involved in SPS and space development activities many years earlier, as described above).

During 2001-2002, NASA continued developing key concepts and technologies for future Space Solar Power applications in the "SSP Concepts & Technology Maturation (SCTM) Program. In the winter of 2002 in particular, NASA, the U.S. National Science Foundation (NSF), and the Electric Power Research Institute (EPRI) issued a joint broad area announcement (BAA) for the SCTM Program that anticipated yielding a number of high-leverage, high-risk research studies targeting some of the key challenges facing future SSP systems. The solicitation sought proposals for projects that would have an impact in one of four key areas:

(1) Radical improvements in wireless power transmission (WPT), with emphasis on solid-state device issues;

(2) More intelligent robotics, allowing assembly of SSP structures in space with minimal use of humans in space;

(3) Improved power management and distribution and control (PMAD), with a special emphasis on reducing system mass; and,

(4) Understanding of costs and opportunities, and how to optimize them, for the net impact on the environment, health and safety, (i.e., to the biosphere the ionosphere, and to sustainable growth around the world).

This program, however useful in terms of specific technical project progress, however, did not lead to ongoing activities by either NSF or EPRI. Some of the individual project studies continued through the end of 2003 when they finally concluded, and with them ended the most recent round of policy-directed US Government Space Solar Power activities.

An Article in Science: Climate Change in an Energy Problem

Climate scientist Dr. Martin (Marty) Hoffert and more than a dozen co-authors (including myself) published a unique article in the journal *Science* in 2002 in which we argued that climate change is fundamentally an energy technology problem that cannot be regulated away.[35] (It took more than eighteen months to work our way through the peer review process and win publication of the journal article.) The article made the point that:

> "Stabilizing the carbon dioxide-induced component of climate change is an energy problem"

And that:

> "Mid-century primary power requirements that are free of carbon dioxide emissions could be several times what we now derive from fossil fuels (~10^{13} watts)"

This was a highly insightful article at the time, when often advocates of action to mitigate climate change focused incorrectly on regulatory solutions. Also in the article, we presented a number of potential technological solutions that might provide dramatic improvements in the GHG emissions per unit energy used – including SPS. It concluded:

> "Potential candidates for primary energy sources include…solar power satellites…"

This was, by the way, the first time that SPS had been mentioned in the pages of *Science* in many years.

International Activities

In the years following 2000, there were several noteworthy international activities to advance the goals of SSP and Solar Power Satellites.

WPT 2001. As described earlier, from the 1980s, CNES had a long-standing program in SSP R&D, lead primarily from the former "advanced concepts group" at CNES headquarters in Paris by M. Guy Pignolet. A significant activity of this team during the late 1990s involved efforts to perform a prototype demonstration of WPT at the French Department of Reunion Island in the Indian Ocean. This effort included a major international meeting (WPT 2001) at the island, and an accompanying international student rectenna competition. However, the proposed major WPT demonstration project did not go forward. (As of Spring 2013, I don't know of any activity related to Space Solar Power at CNES.)

2002: The World Space Congress. In 1992 and again in 2002, the organizers of the IAC (International Astronautical Congress) and those of COSPAR (Committee on Space Research) agreed to hold their annual meetings in conjunction with one another: a World Space Congress (WSC). The 1992 meeting was held in Washington, D.C. while the 2002 meeting was held in Houston, Texas. At the 2002 WSC, the international Space Solar Power community organized a booth in the Exhibition Hall where various results of research – particularly in the US and in Japan – were shown. This was a special opportunity that had not occurred before nor since.

2002-2004 ESA SSP Activities. A year or two after NASA's SERT program, the European Space Agency (ESA) undertook a significant review of the status of Space Solar Power. These SSP studies were organized and led by Leopold Summerer, the chief of ESA's Advanced Concepts Team (ACT), a part of ESA's General Studies Program (GSP). First, ESA published an overarching "SPS Programme Plan". This plan was intended to frame future European research and development related to Space Solar Power.[36] That ESA program was defined to leverage the recently completed work in the US (i.e., SERT), as well as studies such as those at DLR (by Max Seiboldt, and M. Limke); it incorporated what became known as the "SailTower" concept. (See Chapter 4 for additional discussion and an illustration of the concept.)

In this context, Leopold Summerer, based at ESA's ESTEC field center in The Netherlands, did not attempt a bottoms-up analysis of existing, or identification of, new SPS concepts; instead, the central focus of the ESA studies was on a detailed comparison of ground solar power (GSP) and Space Solar Power (the latter based on assumed SPS concepts, largely from NASA's Fresh Look Study). Also, ESA's participation in Japan's 2006 *Furoshiki* sounding rocket experiment (discussed previously) fell under the framework of this activity, as did another experiment attempted in 2012 (which will be discussed in a moment).

SPS 2004 and WPT 5. In the tradition of prior events and as a conclusion of the SSP studies that were then concluding, in 2003-2004 the European Space Agency (ESA) organized a major SSP conference: *SPS 2004*. This meeting, held in Granada, Spain – during 30 June to 2 July – brought together SSP, WPT, and space development advocates and subject matter experts (SMEs) from various countries around the world to review progress toward the realization of the SPS vision.[37] Topics invited for discussion at the conference included: (1) space and terrestrial / planetary solar power plants; (2) integration of solar power from space into a Hydrogen economy; (3) large-scale terrestrial power supply scenarios; (4) wireless and long-distance power transmission; (5) power for space applications (science, research and exploration); and, (6) near-term demonstrations and experiments.[38] This conference brought together experts in SSP and WPT from around the world, as had earlier events in the series.

2006 – The Furoshiki[39] *Experiment*.[40] On 22 January 2006, a truly remarkable low-cost SPS-focused technology experiment was launched on a Japanese S-310 sounding rocket at the Uchinoura Space Center. The experiment was the brainchild of the ever creative and effective Prof. Nobuyuki Kaya of Kobe University, working the in cooperation with a team from the University of Tokyo (Professor Shinishi Nakasuka). Furoshiki incorporated several objectives, including deployment of a large triangular netting in microgravity around a central "mother" section, stabilization of the mesh by three SmallSat "daughter" sections, demonstration of a retro-directive phase control RF system (such as might be used in SPS WPT), and the movement on the netting of tiny robots (provided by the Vienna University of Technology, with support from ESA). Although the brief flight time and net instability limited the success of the experiment, key elements (such as the RF system) worked well, and it was all in all a tremendous accomplishment.

URSI Report on WPT. In 2007, a report on Solar Power Satellites and Wireless Power Transmission was released by URSI (the Union Radio Scientifique Internationale, an international scientific association concerned with the use of radio spectrum. The report, which was principally authored by Prof. Kozo Hashimoto (of Kyoto University, Japan), reviewed a range of different SPS concepts and assessed their potential impact via WPT on radio communications, radio science observations, etc.

SSP Workshop at MIT – Spring 2007

In Spring 2007, The Massachusetts Institute of Technology (MIT) organized, sponsored, and hosted the first independent (i.e., non-government) workshop on SSP in the US in more than a decade. This workshop involved both US government and industry participation, as well as participants from various international organizations. Probably the most important outcome of this workshop was that it informed a first-of-a-kind study of SPS performed for the US Department of Defense (see below); however, it did not result in a published report. MIT has nevertheless continued to conduct R&D in a number of relevant areas such as modular robotics. (MIT has also pursued R&D related to WPT at short range; while related to WPT for SPS, this technology has minimal direct applicability to the transmission of solar energy from SPS platforms to receivers on Earth.)

SBSP (SSP) and the NSSO – 2007

During the middle of the first decade of the 21st Century, the US Department of Defense (DOD) focused increasing attention on the challenge of energy security, and for the first time, DOD stated publicly that energy was an important national security issue. One of the resulting efforts involved an *ad hoc* study performed for the DOD National Security Space Office (NSSO) during 2007 on the topic of "Space-Based Solar Power" (SbSP).[41]

The National Security Space Office (NSSO) was established in May 2004 by combining the National Security Space Architect (NSSA), the National Security Space Integration (NSSI) office, and the Transformational Communications Office (TCO). While it existed, NSSO facilitated the integration and coordination of defense, intelligence, civil, and commercial space activities and is the only office specifically focused on cross-space enterprise issues. NSSO provided direct support to the Air Force, National Reconnaissance Office, other Services and Agencies, Joint Staff, Office of the Secretary of Defense, Office of the Director of National Intelligence, White House, and Congress, as well as other national security space stakeholders.

During 2007, the first-ever DOD-focused study involving Space Solar Power was conducted for the NSSO. The internal coordinator for the effort was Col. Michael (Coyote) Smith; important participants came from the National Space Society (NSS) as well as various individuals, including myself. (I was the science and technology lead for the SPS portion of the study.) This study placed SPS in the context of the increasing need for affordable global energy for DOD use, and the prospects for development of SPS in the coming years. One key aspect of the findings was the idea that although DOD could be markets for SPS power and might support system development through R&D and demonstrations, DOD would not own such systems. The study did not address technical details concerning SPS with any new systems analysis; however, it looked for the first time at issues associated with energy security and the need for energy to assure US military operations around the world.

An impressive amount of press coverage resulted from this modest volunteer effort, in large measure due to the stature of the DOD in the popular imagination and also to the hope that the study delivered to the NSSO might result in funding for SPS development and demonstrations.

Unfortunately for SPS advocates, billions of DOD dollars were not forthcoming, and for unrelated reasons the NSSO itself was reorganized shortly after, ceasing to exist as it had previously.

The Space Enterprise Council

The Space Enterprise Council was a leading industry-sponsored group within the US Chamber of Commerce that for some years promoted the commercial space sector in the U.S. Following the 2007 release of the SSP assessment prepared for the DOD NSSO, the Council took new interest in the topic of Space Solar Power – organizing several briefings and meetings on the topic. A key individual in advancing these discussions was Mr. Paul Eckert, at that time of The Boeing Company. Eckert's approach to SPS was cool and even-handed: seeking to instigate an unbiased systems study, and not unrestrained advocacy.

Without suggesting a particular Agency be responsible, the Council advocated that the US government should undertake a comprehensive systems analysis study addressing the concept of space solar power. The study would have comprised a substantial, end-to-end systems analysis effort examining a wide range of SPS platform topics, as well as supporting infrastructure requirements, and potential market requirements and opportunities. Unfortunately, no decision was made as to whether this study would be implemented before the Council was transferred from the US Chamber of Commerce to the TechAmerica organization.[42] Under its current auspices, the Council has not returned to the subject of Space Solar Power as yet.

Start-Up Companies

After the publicity surrounding the publication of the SbSP study for NSSO (and in the context of the possibility of DOD funding), a number of start-up companies were created. (These companies followed in the footsteps of a handful of earlier entrepreneurial efforts to pursue SSP, such as the Space Island Group.) These included those of Solaren (a US-based start-up), the Space Energy Group (a Swiss-based effort), PowerSat Corporation, and others. The following paragraphs summarize some of the available information about these ventures as it appeared over the past half-dozen years.

Space Island Group. The Space Island Group (SIG) is a small firm based in California that has for more than a decade sought to advance the commercialization of space. (See:

www.spaceislandgroup.com/) Founded by Eugene (Gene) Meyers, SIG published plans to design, build and operate commercial Earth-to-orbit (ETO) transportation systems and to develop in-space platforms (such of which would be assembled from those ETO vehicles) that would be dedicated to commerce, research, space solar power, satellite repair, manufacturing and tourism. SIG's approach to SPS was based on technologies, vehicles, and procedures developed by NASA and aerospace companies since the mid-1970s rather than on new technologies.

During 2005-2008, SIG actively and aggressively pursued a project to build and launch the world's first commercially viable SPS. The purpose of the proposed project was to enable environmentally clean and sustainable energy (in the form of electricity) to be delivered to Earth 24 hours a day with zero pollution. The overall cost to manufacture, launch and assemble the first satellite and its supporting infrastructure was estimated at $10 billion (USD). SIG placed considerable emphasis on graphics and their website; developing various images. However, this organization has been largely inactive during the past several years.

Solaren. Solaren Corporation, based in Manhattan Beach, California (headed by Gary Spirnak, formerly a manager at Boeing Space and Communications), achieved one of the more interesting SSP business model advances.[43] In 2005, Solaren's principals (James Rogers and Gary Spirnak) applied for a patent for a particular type of solar power satellite. This patent was granted in 2009; see US Patent No. 7,612,284. In 2009, Solaren successfully negotiated a first-of-its-kind power purchase agreement (PPA) with the California-based PG&E utility, and won approval from the state's Public Utilities Commission. This was a real accomplishment, but the agreement stated that hundreds of megawatts of SSP power would begin to be delivered as soon as 2016. Based on the agreement, Solar would deliver 200 megawatts of solar energy from space with California utility Pacific Gas & Electric (PG&E). Reportedly, Solaren, Inc. estimated the cost of the first space-based solar system would be $2 billion for 200 megawatts (i.e., roughly $10 per watt). The company asserted that it will have the system in operation in GEO by 2016. Surprisingly, Solaren stated that its SPS design will require only four expendable launch vehicles (ELVs) to send it into orbit.

The organization has no known existing R&D staff or organization; in order to implement its project objectives, contracting with other organizations would most likely be necessary. Although still vocal (Spirnak was interviewed for an IEEE web-zine in January 2013), there are evident signs of SPS contracts or construction as yet.

Space Energy Group. The Space Energy Group (SEG), based in Switzerland, emerged around 2007-2008 and is somewhat related to its homophonic predecessor, the Space Island Group – at least through its principals. Space Energy took an interesting approach to SSP: the firm invested considerable time and effort in cultivating a potential market for SPS power in China, including attempting to obtain a power purchase agreement (PPA), following the model established by Solaren in California. Unlike several other SSP related start-ups, the website for the Space Energy Group provides considerable information about Space Energy and its activities. However, the SEG appears to have no particular technical approach, nor intellectual property related to SPS. Space Energy's technical strategy is to operate as an SPS systems integrator, providing project management in the design, procurement, manufacture, deployment, and operations of future SPS.

Planetary Power. Planetary Power, Inc. is another SSP-related start-up firm, based in Vienna, Virginia (USA); it was founded c. 2007-2008, apparently with funding from Space Adventures founder Eric Anderson, who appears to be the owner of the firm. (See http://planetarypower.com/.) The President of the firm is identified as John Kohut, formerly the lead for SSP-related business development at Raytheon Company (and one time US Navy officer). The website provides no information on space activities, but only on its terrestrial power technology objectives. In addition, Mr. Roger Lenard (also affiliated with the US Air Force Research Laboratory) is identified as associated with Planetary Power, Inc.

Planetary Power is working on various terrestrial energy technologies as well as pursuing SSP. In particular, during summer 2010, the firm filed for a trademark for the phrase "POWER GRAIL," which was identified as "bulk energy storage device." Also during summer 2010, the firm filed for a trademark for the term "SUNSPARQ." which was identified as a "solar powered electricity generator" and as a "concentrated solar power system" that would involve a "collector array." Planetary Power also appears to be a member of the American Council On Renewable Energy (ACORE).

PowerSat Corporation. PowerSat Corporation, PowerSat Ltd, and PowerSat International are various names that are apparently used for the same SSP venture, based in the USA, UK, and Gibraltar.[44] PowerSat, founded by William E. Manness (CEO) in 2001, has asserted a concept described as "Brightstar," which involves use of a constellation of non-physically contiguous microwave SPS operating at 5.8 GHz. Technical studies were conducted by Maness and Janet

Hendrickson. No explanation is offered as to how grating lobe losses due to the sparse character of the WPT transmitter will be resolved. PowerSat estimates a cost of roughly $3-4 Billion for a 2,500 megawatt SPS power plant; however, it seems likely that this is a significant understatement of the likely costs.

It was reported on-line that PowerSat Corporation obtained $3-to-$5 million in angel investment funding in 2008. PowerSat Corp. in the US is reported to be a partner of PowerSat Limited in London and a subsidiary of PowerSat International in Gibraltar. The firm filed U.S. Provisional Patent No. 61/177,565 for "*Space-Based Power Systems And Methods*." The company apparently plans to begin the proof of concept process with a 10-kilowatt demonstration of wireless power transmission capability on Earth, and is seeking further financing in "the single-digit millions." PowerSat Corp. hopes to launch a $100 million, low-earth-orbit project by 2015 and partner with a utility or government agency on a utility-scale project of ~2.5 gigawatts, at a cost of $4-to-$5 billion, between 2019 and 2021. (By the way, it seems likely that "PowerSat Corporation" was closely related to "Orbital Power Corporation," listed separately; however, the relationship was unclear.) Despite the evident enthusiasm, none of these ventures appears to have resulted in significant progress toward SPS development.

Heliosat. Heliosat, Inc. was another announced SSP-focused start-up company, apparently formed circa 2007-2008. The Heliosat plan was to use SSP to develop America's abundant shale oil resources. This plan apparently captured some level of the interest of the Greater Houston Partnership, and of some of its oil and gas membership. This business model would employ the relatively small amounts of power from space to leverage a larger ground-based energy source. Key personnel involved in Heliosat include Joe Burris (identified as CEO of the firm) and Roger Lenard (now part of the team at Planetary Power, discussed elsewhere). In one article, it was suggested that the Heliosat SPS technical strategy was to use microwave wireless power transmission, combined with concentrating solar thermal turbo-generator (rather than PV), where the receiver heats an argon-helium working fluid and a specially designed vacuum facing radiator functions as the condenser. The concept appeared to involve launching multiple concentrator and solar dynamic power modules to LEO, from where they would be transported to GEO via some type of space-based rotating tether system.

Versatility Software, Inc. Versatility Software, Inc. is a small firm based in New Jersey, working principally in software development that was founded by Eric Hoffert, son of Dr. Martin

("Marty") Hoffert, a climate scientist and well-known advocate of SPS using laser-based wireless power transmission.[45] Through Versatility, Inc., the senior and younger Hoffert seek to "drive R&D concepts and technology development to radically advance the state of the art of 21st Century Energy options, including renewable, alternative energy systems (both terrestrial and space based) and new approaches to efficient energy distribution and management."

Through its company strategy vis-à-vis SSP, Versatility, Inc. focused on specialized applications of Space Solar Power. Niche markets include peak power for developed nations, combined power and data delivery, and providing power to developing nations. Potential customers include energy providers such as utilities and direct end-users such as governments and corporations. The company's current strategy is to focus on government and industrial R&D grants and contracts and to build up the company in a profitable manner. The firm's stated long-term plan was to become the world's leading provider of SSP through winning market leadership in a succession of niche markets – ambitious goals, indeed. However, thus far there is no indication of progress toward those goals.

2008: A First-of-a-Kind Demonstration of SPS Technologies

With sponsorship from Discovery Communications, one of the several SSP-related start-up companies – Managed Energy Technologies[46] – put together an international team to conduct a first-of-a-kind demonstration of end-to-end SPS WPT technologies from the crest of Haliakala to the slopes of Mauna Loa – a distance of a bit less than 100 miles (148 km). See Figure 3-5.

This demonstration project was presented as an episode on the Discovery Channel series "Project Earth" in autumn 2008. The team involved myself as project lead, Prof. Nobuyuki Kaya and his team from Kobe University with responsibility for the wireless power transmitter, Dr. Neville Marzwell, formerly of the Jet Propulsion Laboratory with responsibility for a solar power generation system, and Dr. Frank Little and a team at Texas A&M University with responsibility for WPT system testing and for providing detectors for a field test of the end-to-end system in Hawaii.

Figure 3-5 Solar-Powered WPT Demonstration in Hawaii – May 2008

2008: ISS-Based WPT Demonstration Proposal Development at NASA

Also during 2008, there was a 9-month effort led by the NASA Johnson Space Center (JSC) to define a potential International Space Station (ISS) based WPT demonstration. NASA partnered with the DoD and collaborated with industry and academia in developing the demonstration concept using the Space Shuttle for transportation and the ISS as a test platform. The plan was to develop the demonstration rapidly so that it could be launched on one of the last Space Shuttle flights to the ISS. The demonstration would have been a WPT test from LEO to the Earth. Because NASA planned to retire the Space Shuttle by the end of 2010, work on the demo required a highly accelerated track if there was to be an opportunity before Shuttle flights ceased. This schedule required the use of existing power beaming assets, hardware, and software to meet test objectives. Ultimately, this WPT demonstration project did not go forward, due both to budget requirements and to the retirement of the Space Shuttle.

SPS 2009 in Toronto

Following in the footsteps of earlier events, including the SPS 2004 conference in Spain discussed previously, an international conference – SPS 2009 – was organized in Toronto, Canada in that year. This meeting was organized as a key event in the implementation of a then ongoing study of SSP by the International Academy of Astronautics (This study is described in greater detail later).

An important element of this event was a live demonstration of WPT by Prof. Nobuyuki Kaya and his team from Kobe University. This exciting test proved the technology of retrodirective phase control for electronic WPT beam steering to a moving target. Moreover, this international workshop was the centerpiece of the first international assessment of Space Solar Power.

The SPS 2009 International Symposium and Conference would never have happened without the support of a new organization interested in SSP – SPACE Canada. SPACE Canada (aka, "Solar Power Alternative for Clean Energy" Canada) was founded in 2008 as a not-for-profit organization dedicated to the promotion of international dialog on the topic of solar energy from space, an abundant and sustainable source of safe, affordable clean energy for the world. SPACE Canada's mandate is to support, encourage, and facilitate international dialogue on solar energy from space (via SPS) through education, research, and commercialization. SPACE Canada's mission is to be a leader in the promotion of solar energy from space as a sustainable and renewable source of clean energy, thus enabling a dramatic reduction in the world's dependence on carbon-based fossil fuels.

SPACE Canada worked as a major sponsor with the IAA "First International Assessment of SSP" study group to organize and implement the SPS 2009 event. SPACE Canada was also the principal sponsor for the publication of the final report from the IAA study, discussed below. SPACE Canada continues to pursue opportunities to promote SSP and various related technologies (e.g., WPT) and their nearer-term applications.

2010: WPT Experiment in Hawaii

In early summer 2010, another wireless power transmission experiment was performed by an international team comprising Prof. Nobuyuki Kaya and students and staff from Kobe University and John C. Mankins from Artemis Innovation Management Solutions LLC, a consulting firm in California. This experiment followed on the WPT demonstration performed in 2008, but using the hardware from the highly successful test of retrodirective phase controlled wireless power transmission at the SPS 2009 symposium (both described previously).

2008-2011 IAA Study

The International Academy of Astronautics (IAA) undertook one of the more significant SSP-related activities of the past decade: "The First International Assessment of Space Solar Power." Chartered by Commission III of the Academy during 2008-2011, this integrated but high-level systems study was implemented and reviewed by a team comprising some ten (10) different countries.[47] The overall goals of the study were to determine what role solar energy from space might play in meeting the rapidly growing need for abundant and sustainable energy during the coming decades, to assess the technological readiness and risks associated with the SPS concept, and (if appropriate) to frame a notional international roadmap that might lead to the realization of this visionary concept.

The final report from the study (which I edited) identifies potential markets and policy issues, and examines three distinct architectural approaches to SPS – including a updated technology version of the 1979 SPS Reference System, a modular laser WPT system concept, and a hyper-modular microwave WPT concept. It also frames the first international consensus roadmap for the development of the SPS concept. Available from the IAA, the report concludes with a integrated set of findings and recommendations to the international community on Space Solar Power.

Activities in India

A long-standing space systems program manager in India, retired Air Commodore Raghavan Gopalaswami (Former Chairman & Managing Director of Bharat Dynamics Ltd, of Hyderabad, India) has for many years advocated the joint coordinated development of Space Solar Power and Reusable Launch Vehicles.[48] During the past several years, there have been a number of intriguing statements of support for SSP by various leaders and organizations in India. The most senior of these have involved the former President of India, Dr. Abdul Kalam.

Dr. Kalam has repeatedly taken strong positions in support of the joint development of Space Solar Power and air-breathing Reusable Launch Vehicles (RLVs). Both the India Space Research Organization (ISRO) and the Indian Defense Research and Development Organization (DRDO) expressed potential interest in SSP during 2007-2008. DRDO in particular was forthcoming in its potential interest, including an offer to co-sponsor an SSP systems analysis study with the US in 2007-2008. This systems analysis did not take place; however, to my knowledge no specific SSP studies and/or technology development R&D were initiated. Additional developments concerning Dr. Kalam and the NSS are described later.

Since 2010…

During the past several years there have been several flurries of activity related to SSP in the US and Europe, sometimes involving government activities but more typically new commercial ventures interested in pursuing SSP. There has also been continuing steady technology progress – albeit at a low level of funding – in Japan.

SSP Developments in Japan

The terrible earthquake and resulting deadly tsunami near Tokyo on March 11, 2011 were significant for SSP in the Japan in two contradictory ways. First, the disaster was quite negative for SSP R&D because discretionary budgets for longer-term topics such as this were brought under severe scrutiny as money was sought for urgent near-term recovery and reconstruction projects. On the other hand, the disaster made it clear that new energy sources, such as Solar Power Satellites, were needed for the future, and this promoted maintaining the Japanese investment in SPS. Overall, work on SSP has been slowed, but has continued during the past several years (to 2013).

Most importantly, the recently restructured “Basic Space Law” of Japan (dataed January 2013), continues to include Space Solar Power as a goal of Japan’s space program. I was fortunate in September 2013 to discuss SPS in meetings with a member of Japan’s Congress and with the head of the Space Industry Division of the Ministry of International Trade and Industry (MITI); both gentlemen expressed strong continuing interest in Space Solar Power.

SSP Developments in Europe

SSP and ESA. After a hiatus of several years, ESA is looking at the possibility of revising Space Solar Power. Aspects of this potential new effort would be considered in terms of the "20-20-20" Energy policy of the European Union, the significant changes in the international energy marketplace (described in Chapter 2), and the potential for an orbiting demonstration before 2020. The possible new ESA effort would continue to emphasize economics and integration of SSP into overall terrestrial energy markets.

In this context, in early 2012 a European sounding rock experiment was launched, named "Suaineadh," which attempted the spin-stabilized deployment of a structural mesh such as might be used as a scaffold for a future SPS (or other large aperture) deployment in space. The Principal Investigator, Dr. Massimiliano Vasile (formerly of the University of Glasgow, and more recently of the University of Strathclyde) has been involved in ESA Advanced Concepts Team activities for some years. Although the experiment did not succeed, it illustrated the type of small-budget, highly focused technology experiment that ESA has been pursuing vis-à-vis SPS related R&D.

EADS Astrium – Laser WPT SSP Demonstration Planning, The European Aeronautic Defense and Space (EADS) Company is the largest aerospace company (and government contractor) in Europe. Astrium, a subsidiary of EADS, is the large space company and has for a number of years pursued studies – both independent and funded by the European Space Agency (ESA) – related to Space Solar Power.

One concept explored by Astrium in 2010 was that of an initial 10 kW-delivered laser WPT GEO satellite demonstrator.[49] In this planning, the demonstration satellite would provide power to ground users by ground user by the 2020 horizon. The concept is for the GEO satellite to be compatible with launch on a single Ariane 5 expendable launch vehicle (which has a maximum launch capacity of up to 10,000 kg to GTO with an advanced cryogenic upper stage option). Several new technologies would be required for the concept.

SSP and China

There have been a number of SSP and related R&D activities in China during recent years. These have included focused, internal SSP research and development (R&D) efforts, as well as selected international outreach activities. Several years ago, these involved in particular the

Switzerland-based, European company, the "Space Energy Group" (SEG); however, there don't appear to be any recent activities involving this group in China.

During Spring 2010, a conference was held in Chengdu, Sichuan Province, entitled the "Sichuan International Clean Energy Summit" (SICES 2010). This meeting, which was co-organized by the SEG and held during 12-14 April 2010, involved a number of participants from the US, Europe and China. Its goals were to bring together top experts from China, the European Union, the United States, and others for discussions on China's strategic options for high-tech derived clean energy projects. In particular, the forum sought to advance the understanding of paradigm-changing approaches for clean and sustainable energy development via commercialization of frontier technologies – including the topic of SPS.

SICES 2010 comprised the following topics: background and history of SPS; discussion and comparisons among alternative novel energy solutions (including SPS) for the medium to longer-term; developments in the energy industry and advanced energy technologies in China; discussion of Chinese SPS R&D activities; and potential business discussions among participants.

The China Academy of Space Technology (CAST) conducted research related to Space Solar Power for the past several years. CAST performed initial feasibility studies of SPS, developed a conceptual design, and conducted technology R&D [all with funding from the Ministry of Industry and Information Technology (MIIT)]. From these efforts, prototypes involving both microwave and laser WPT are being developed (technology maturity unknown). Specific research topics that have been examined in China as part of recent SSP and related technology research and development in recent years include: (1) overall concepts and general feasibility of Solar Power Satellites; (2) specific technologies for SPS, including wireless power transmission and others; and, (3) SPS technology development and demonstration plans, programs, and results. During 2012, past-President of India, Dr. Abdul Kalam, attended a meeting on SSP and energy in Beijing, China. While there, Kalam was invited by the Chinese event organizers to consider forming a joint China-India program to develop the Solar Power Satellite concept, including necessary supporting systems.

And, during the past several years, Chinese researchers have begun participating for the first time in the long-standing IAF Power Symposium at the annual International Astronautical Congress (IAC; described previously). At the 2013 IAC, held in Beijing, China, the first-ever

IAC Space Solar Power ‘Plenary Event’ was held, organized by myself and Leopold Summerer of ESA with the support of Dr. Li Ming of CAST. These Congress-wide, hour-long sessions attracted an audience of over 300, and involved speakers from China (Prof. GE Chang-Chun, a member of the China Academy of Sciences), the European Space Agency (Isabelle Duvaux-Bechon, ESA Head of Prospective Studies), Japan (Prof. Nobuyuki Kaya from Kobe University), and the US (myself).

US Activities

Naval Research Laboratory – WPT Sandwich Panel Project. The US Naval Research Laboratory (NRL) evinced some interest in the possible development of SPS in the nearer-term. During Summer 2008, NRL conducted an internally funded review of systems concepts, technologies, and prospects for SPS in the nearer term. As a result of this effort, the Laboratory approved funding for an initial project, the objective of which is to develop and demonstrate selected SPS technologies focusing on an integrated solar power-WPT sandwich panel demonstration. This project, which started in 2009, will be concluding in 2013 with testing of several WPT sandwich panel test articles with Mr. Paul Jaffe of NRL as the principal investigator for the effort.

Solar High. During 2011-2013, an informal group known as “Solar High” formed for the purpose of promoting SPS – with an emphasis on the space transportation aspects of the required technologies.[50] The Solar High group is unique in the present SPS community in advocating for a technology update, but no architectural changes from the systems concept of the 1970s. Members of the group include many good friends and associates, including Phil Chapman, Sc.D. (former Apollo scientist-astronaut and President of the L5 society), Hu Davis (NASA JSC, retired), Dick Dickinson (NASA JPL, retired), Brigadier General James Freytag (USAF, retired), Feng Hsu, Ph.D. (NASA GSFC, retired), Lieutenant General Dirk Jameson (USAF, retired), Ralph Nansen (Boeing, retired), Theodore (Ted) Talay (NASA LaRC, retired), and Gordon Woodcock (NASA MSFC and Boeing, retired).

NIAC and the SPS-ALPHA Concept. And, in Spring 2011 NASA’s recently reconstructed Advanced Innovative Concepts (NIAC) Program issued its first call for proposals.[51] One of the responses which was selected for funding was entitled “SPS-ALPHA (Solar Power Satellite by means of Arbitrarily Large Phased Array). This concept, which I proposed, expands on the strategies first articulated during NASA's Fresh Look Study of SSP in the 1990s, and is an example of a new hyper-modular approach to SSP. SPS-ALPHA presents an important new architectural approach to the vision of the Solar Power Satellite, and is discussed in considerable detail later in this book (for example, see Chapter 10 and subsequent chapters).

The final report from this Phase I NIAC study project was delivered to NASA in September 2012.[52]

ISDC 2012 and 2013. For the past half-dozen years, the National Space Society has appeared several times in the story of Space Solar Power both in the US and internationally. In May 2012, at the NSS annual International Space Development Conference (ISDC) in Washington, D.C., Dr. George C. Nield of the Federal Aviation Administration (FAA) gave a speech that recalled the famous words of President John F. Kennedy in 1961. Nield offered – in discussing the future of space transportation – some visionary thoughts regarding events that the years before 2019 might see.[53] Among his predictions, he included:

> "We may also see a commercial proof of concept space solar power demonstrator that can transmit power from outer space to collection stations on the ground."

It is remarkable that Nield should mention SSP in his remarks regarding the future of space transportation. (I believe that it bodes well for the future.)

Kalam-NSS Initiative. Also, for several years the NSS has been involved in a discussion with the former President of India, Dr. Abdul Kalam, which resulted in agreement on what became known as the "Kalam-NSS Initiative." The focus of the agreement is on a proposed international collaborative systems study on the topic of Space Solar Power. Although this study has not been funded as of this writing, nevertheless the relationship has proved an important one. In May 2013, Dr. Kalam attended and spoke at the NSS International Space Development Congress (ISDC) held in San Diego, California at the end of May 2013. During the ISDC event, Kalam gave the keynote address at the Gala Dinner and formally proposed – jointly with the Society – the formation of a new international study of SSP. It remains to be seen if this new push will gain traction among the international community, but it was certainly a step in the right direction.

One More Thing… There has also been recent interest in wireless power transmission using high frequency RF or laser, particularly in the US but also to some extent in Japan and Europe (see note about EADS above). The latter option sometimes includes the potential of using an extremely high-power laser for Earth-to-orbit transportation. It is my view that these architectures are *not* preferable in terms of economics to a highly modular microwave WPT SPS architecture, and that they are in fact seriously flawed from a geopolitical standpoint. Chapter 4 will explore additional the details on some examples of this class of SPS concepts – and make clear why I do not believe they are on the path to affordable, abundant Space Solar Power in space and on Earth.

A Quick Recap

The history of Space Solar Power in general (and Solar Power Satellites in particular) is distinctly episodic. Although the concept of the SPS was first conceived almost fifty years ago, the idea has never truly become "part of the program" despite periodic attention by various groups and governments. SPS continues to be a uniquely polarizing topic among aerospace professionals, with some being firmly in favor of the Space Solar Power vision, and others adamantly opposed to even discussing the idea, much less supporting it through R&D.

Although the concept of the SPS was invented in the US, at present the most significant ongoing activities at present are in Japan and China, two countries with very different economies and demographics, but with a common and strong interest in preparing strategically to meet their respective future energy needs.

One topic that often arises with regard to SSP in the US is this: what about the Department of Energy (DOE)? In the 1970s, the then newly formed DOE was tasked to lead studies and R&D targeting on SPS. However, the result of these efforts was far from promising. In general, space is not DOE's job in the US Federal Government, just as energy is not NASA's job. SSP/SPS falls neatly "between the cracks" in Washington: it is no one's job. More recently, the creation of the new "Advanced Research Projects Agency for Energy (ARPA-E) in the DOE has led many to hold new hope for DOE becoming involved once more. However, although several concept papers related to SSP were submitted to ARPA-E when it issued its first large-scale open call for ideas in 2009, none of these were selected for consideration and/or funding. Since then, ARPA-E has issued various solicitations and has funded diverse additional projects, but these calls for proposals have been almost entirely targeted on specific topics of interest in terrestrial energy technologies (not SSP), and none of the projects funded addressed SSP. This is not surprising: the field of energy is enormous; there is a tremendous array of technology challenges to be solved. There are also no champions inside the DOE organization for an idea quite so "out-of-the-box" as Space Solar Power. Moreover, in 2009 the then-Secretary of Energy (Dr. Steven Chu) stated during a meeting in India that he had not been persuaded that SPS are viable. Shortly after the beginning of 2013 (with the start of President Obama's second term in office), Secretary Chu left the leadership of DOE; it remains to be seen whether the appointment of his replacement, Secretary Ernie Moniz (from MIT) will result in a change in the prospects for future DOE interest in Space Solar Power. (But I certainly hope so.)

The preceding discussion has been by no means comprehensive; there are a great many details – of organizations, people, and technological accomplishments – that have been omitted or treated with brevity. It should, however, provide the foundation we need to understand better why we are where we are with respect to Space Solar Power. In other words, why the idea of the Solar Power Satellite, proposed more than 45 years ago, has never received the levels of interest or of funding of other technologies during those decades. And, yet, despite this lack of focused investment (or perhaps because of it) the SPS concept has made more progress than most people know.

In reviewing the history of SSP, we touched briefly a variety of different Solar Power Satellite systems concepts and technology options. The next chapter turns to these technical aspects of Space Solar Power. What are the constraints on SSP or WPT? What are the options for SPS systems concepts? And, most important, how can we get to solutions that might actually be achievable?

[3-1] Santayana, George; "The Life of Reason," Volume 1. 1905-1906. This very famous quotation inspired a number of others to paraphrase the observation, including Winston Churchill…!

[3-2] Versions of this humorous and well-known saying are attributed by most to famous (but not very funny) Danish quantum physicist Neils Bohr, and also to famous <u>and</u> funny Baseball coach Yogi Berra. See: http://www.peterpatau.com/2006/12/bohr-leads-berra-but-yogi-closing-gap.html

[3-3] Glaser, P.E., Davidson, F.P and Sigi, K.I., "Solar Power Satellites: the Emerging Energy Option," (Ellis Hordwood, New York, New York). 1993.

[3-4] Office of Technology Assessment, US Congress, "Solar Power Satellites," (Washington DC.). 1981.

[3-5] Throughout this Chapter, and elsewhere in this book, I have attempted to highlight the roles and activities of various individuals and organizations that have been important in the origination and development of Space Solar Power. I am sure that I have missed some, for which I apologize in advance. Please feel free to call these omissions to my attention and I will try to correct them in a later update of this text.

[3-6] Sir Hnery Tizard was a senior scientist in Great Britain in the 1920s-1940s, and an advocate of sharing novel technologies that might help win World War II with the US. See: Phelps, Stephen, "The Tizard Mission," (Westholme Publishing LLC, Yardley, Pennsylvania). December 2010.

[3-7] William C. Brown (Raytheon, retired) to Ivan Bekey (NASA); *Personal Correspondence*. 21 May 1995.

[3-8] Bill Brown wrote a focused history of WPT in the early 1980s; for additional information on this fascinating technology, see: Brown, William C., "The History of Power Transmission by Radio Waves," (IEEE Transactions on Microwave Theory and Techniques, Vol. MTT-32, No. 9; pp. 1230-1242). September 1984.

[3-9] The topics of WPT and atmospheric absorption of EM energy are discussed in detail in Chapter **4**.

[3-10] Anon., "Microwave power transmission: a brief history," (*Popular Science* Magazine, p. 65). January 1988.

[3-11] A "diode" is an extremely simple and fundamental bit of electronics that is somewhat like a malevolent traffic cop: at the point where it is located in an electronic circuit, the diode only allows electricity to flow in one direction, but not in the other; hence, an alternating current (moving alternatively one way and then the opposite) is neatly turned into a direct current (moving only one way). There are some additional details, but that is the gist.

[3-12] For example, see: http://astronauticsnow.com/history/goddard/index.html. The New York Times eventually published a belated correction on 17 July 1969, three days before the historic Apollo 11 Moon landing – but no apologies to the then-deceased Goddard, who had been driven into seclusion to continue his experiments by the fierce and unjustified criticism.

[3-13] See: http://en.wikipedia.org/wiki/Photoelectric_effect. Heinrich Hertz first observed the photoelectric effect in 1887; however, it was Einstein who received the Nobel Prize for his seminal 1905 paper explaining the effect.

[3-14] See: http://en.wikipedia.org/wiki/Solar_cell

[3-15] Glaser, Peter E., "Power from the Sun: It's Future," (*Science* magazine; pp 857-861, Volume 162, Number 3856). 22 November 1968. This paper was adapted from Dr. Glaser's August 1968 presentation at the Intersociety Energy Conversion Engineering Conference (IECEC) in Boulder, Colorado.

[3-16] I highly recommend Dr. Glaser's original paper to any who are truly interested in SPS. It is very interesting to compare this 1965 version of an SPS to the version that appeared (see Figure 3-1) in Dr. Glaser's 1968 patent application. In particular, the 1965 spherical solar array becomes a pointed disc array by 1968, and the superconducting PMAD is no longer emphasized; changes that reflect satellite developments in the 1960s.

[3-17] Phillip K. Chapman, "Press Misinterprets NRC Report on SPS" (L5 News; Princeton, New Jersey). December 1981.

[3-18] See: http://www.spacefuture.com/archive/japan_the_21st_centurys_energy_supplier.shtml.

[3-19] Hu Davis' recent role in the promoting SPS through the "Solar High" group is discussed below.

[3-20] See Nansen, Ralph, "Sun Power - The Global Solution for the Coming Energy Crisis" (Self-Published). 1995.

[3-21] See Maynard, Owen E., "Solid State SPS Microwave Generation and Transmission Study, Volume I, Phase II Final Report, (NASA Contractor Report 3338, Contract NAS8-33157). November 1980.

[3-22] See, for example: http://en.wikipedia.org/wiki/Gerard_K._O%27Neill

[3-23] See: http://en.wikipedia.org/wiki/International_Space_University.

[3-24] SSP Project Team, "Space Solar Power Program Final Report," (International Space University, Kitakyushu, Japan). August 1992.

[3-25] Shea, Joseph F., Chair; "Space Technology to Meet Future Needs," (Committee on Advanced Space Technology, Aeronautics and Space Engineering Board (ASEB), National Academy Press, Washington, D.C.; pp 86-94). 1987.

[3-26] As it happened, in the fall of 1987 I first went from JPL to work at NASA Headquarters; my assignment was to serve as program manager for a new program called "Project Pathfinder," the goal of which was to develop technologies to enable future human and robotic space exploration. Although space nuclear power figured prominently in the portfolio, no one spoke of Space Solar Power, and I was quite unaware that SSP had ever been a topic for consideration.

[3-27] Space Research Associates, Inc., "Solar Power Satellite Built of Lunar Materials" (Final Report). 21 Sept. 1985.

[3-28] Reference: National Commission on Space Report (1986), pp. 82-83.

[3-29] Interestingly, the Commission also highlighted the still-underrated worries that were emerging concerning global warming: "From an environmental viewpoint, we suspect that the continued dumping of fossil fuel

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emissions into the atmosphere (primarily carbon dioxides) have significant effects on Earth's biosphere," opening the door for future developments in nuclear power and Solar Power Satellites.

[3-30] Reference: National Commission on Space Report (1986).

[3-31] Lunar Energy Enterprise Case Study, "Report of the NASA Lunar Energy Enterprise Case Study Task Force," (NASA Technical Memorandum 101652). July 1989.

[3-32] As a result of a rather complex set of circumstances, I was fortunate to serve as the technology lead for the "90-Day Study," kicked off by President Bush's 1989 speech. The only significant energy technology option included was that of nuclear power and propulsion. In fact, there was a strong opinion among the leadership of the 90-Day Study that only a small number of technologies should be emphasized – thus keeping the "story" simple. SSP never had any chance to be considered for that short list.

[3-33] Blacic, James D., Ph.D., "Extraterrestrial Resources and the Space Exploration Initiative, a Department of Energy Perspective," (US Department of Energy Presentation to NASA; Washington, DC). October 1990.

[3-34] See: NRC, "Laying the Foundation for Space Solar Power – An Assessment of NASA's Space Solar Power Investment Strategy," (Committee for the Assessment of NASA's Space Solar Power Investment Strategy, ASEB / NRC, National Academy Press, Washington, D.C.). 2001.

[3-35] Hoffert, Martin I., et al., "Stability: Energy for a Greenhouse Planet Advanced Technology Paths to Global Climate," (*Science*, Volume 298, pp. 981-987). 1 November 2002.

[3-36] Summerer, L. and Jacque, L., "Prospects for Space Solar Power in Europe," (62nd International Astronautical Congress, IAC-11-C3.1.3; Cape Town, South Africa). October 2011.

[3-37] As it happened, I was not able to attend the SPS 2004 conference in Spain. I was still at NASA Headquarters at that time. Following the loss of Space Shuttle Columbia in January 2003, I became actively involved in framing plans for what became the technological aspects of the "Vision for Space Exploration" (VSE) announced in early 2004. When the time came for the SPS 2004, I was in the midst of deploying an essential element of the VSE: the Exploration Systems Research and Technology (ESRT) program, which I managed.

[3-38] See: http://www.esa.int/gsp/ACT/events/workshops/sps04.htm

[3-39] "Furoshiki" is a Japanese word that refers to a large folding cloth – such as might be used to bundle together the meager possessions of an itinerant.

[3-40] See: Summerer, L., Kaya, N., et al, "First results of Robots Crawling on a Loose Net in Microgravity during a Sounding Rocket Experiment," (International Astronautical Congress; IAC-06-C3.3.05; Valencia, Spain). October 2006.

[3-41] "Space-Based Solar Power As an Opportunity for Strategic Security; Phase 0 Architecture Feasibility Study," (Report to the Director, National Security Space Office). 10 October 2007. For a downloadable copy of the report, see: http://www.nss.org/settlement/ssp/library/nsso.htm

[3-42] For additional information about the Space Enterprise Council, see www.techamerica.org/space

[3-43] If interested, you may wish to glance at: www.spaceenergy.com/. However, the last time I checked in early 2013, no information is provided there.

[3-44] For additional information, see: http://www.powersat.com/.

[3-45] See: http://www.versatility-inc.com/.

[3-46] The start-up Managed Energy Technologies LLC pursued a number of advanced energy technologies from 2006 into early 2010, when it was dissolved.

[3-47] Commission III is the technical commission that addresses space systems and technology development related matters for the Academy. See: Mankins, John C., Editor; "The First International Assessment of Space Solar Power: Opportunities, Issues And Potential Pathways Forward; (IAA Publication; Paris, France). September 2011.

[3-48] See: R. Gopalswami, "Sustaining India's Economic Growth," (Online Journal of Space Communication; Issue 16: Alternative Energy). Winter 2010. Also see: http://spacejournal.ohio.edu/issue16/gopal.html.

[3-49] The results of the study reported here were presented at the IAC 2011 in Cape Town, South Africa.

[3-50] For more information about this group, see: http://solarhigh.org/AboutUs.html

[3-51] The current NIAC is the successor of a prior program / organization with the same acronym, but a slightly different definition, the NASA Institute for Advanced Concepts, which based in Atlanta and headed by Dr. Robert (Bob) Casanova for NASA. This earlier NIAC was itself the successor of the 1990s era Advanced

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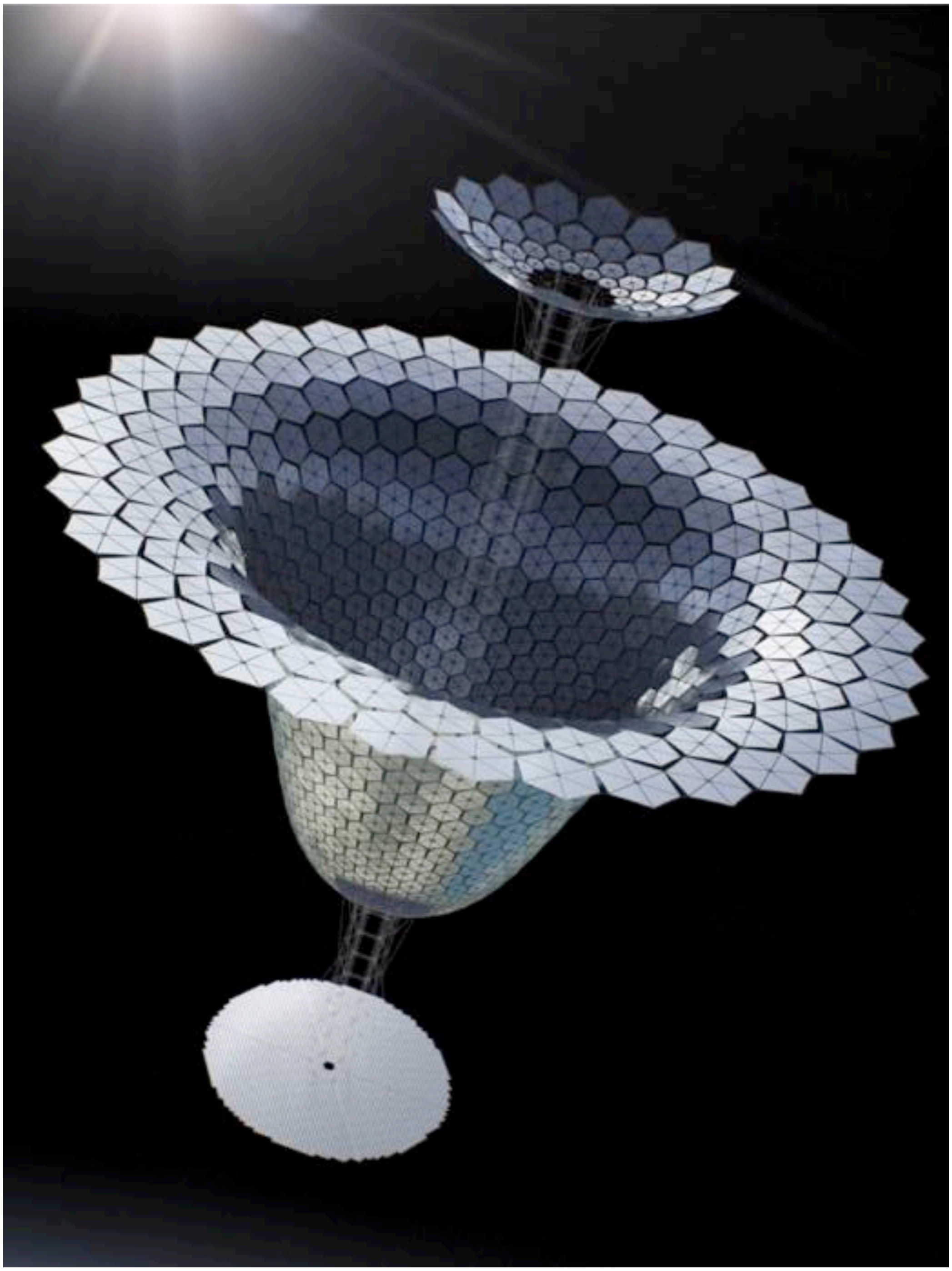
Concepts Office at NASA Headquarters. This was the office where I worked in 1995 when I was assigned to conduct what became known as the "Fresh Look Study."

[3-52] See: http://www.nasa.gov/pdf/716070main_Mankins_2011_PhI_SPS_Alpha.pdf

[3-53] See: Nield, George C. "Before this Decade is Out," (Speech at the NSS ISDC; Washington D.C.). May 2012.

Part II

Solving the Problem of Space Solar Power



Chapter 4

What are the Options?

Considering Various Solar Power Satellite Concepts

> *"To place a man in a multi-stage rocket and project him into the controlling gravitational field of the moon where the passengers can make scientific observations, perhaps land alive, and then return to earth - all that constitutes a wild dream worthy of Jules Verne. I am bold enough to say that such a man-made voyage will never occur regardless of all future advances."* 1
>
> *Lee DeForest (1926)*
> *American radio pioneer and inventor of the vacuum tube*

Introduction

As suggested by the quick history sketched in the previous chapter, Space Solar Power *might* be implemented in any one of an extremely wide variety of ways. However, not all of these ways are technically feasible, and of those that are feasible, fewer still are likely to prove economically viable. Moreover, of those SPS concepts that are technically feasible *and* economically viable, not all may be acceptable candidates programmatically or geopolitically.

This Chapter describes several major different types of SPS system architectures, including the well-known 1979 SPS Reference System (introduced earlier); it then evaluates these different SPS options (and several other approaches to Space Solar Power) with the objective of focusing on the sort of satellite concept that is likely to be the most promising.

It begins by summarizing the physical constraints and technical challenges that must be considered, including some of the intricate engineering relationships among SPS system elements.

*So **you** want to design a Solar Power Satellite?*

There are lots and *lots* of different – and often interrelated – issues to be considered. These issues fall into two broad categories: engineering and technology-related factors, and physics-based constraints on SPS functionality and architectures. Let's begin with the latter: physics-based constraints.

Physics-Based Constraints

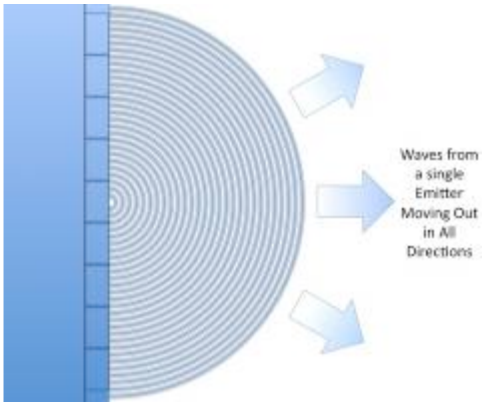
There are a number of external physical constraints that cannot be avoided; these constraints frame the system and deployment choices that might be made for any SPS concept. A handful of these dominate any effort to devise an SPS, and among the most important of these physical constraints on a Solar Power Satellite is that of the physics of electromagnetic (EM) wave propagation and the consequences of this physics for wireless power transmission.

Diffraction-Limited Optics

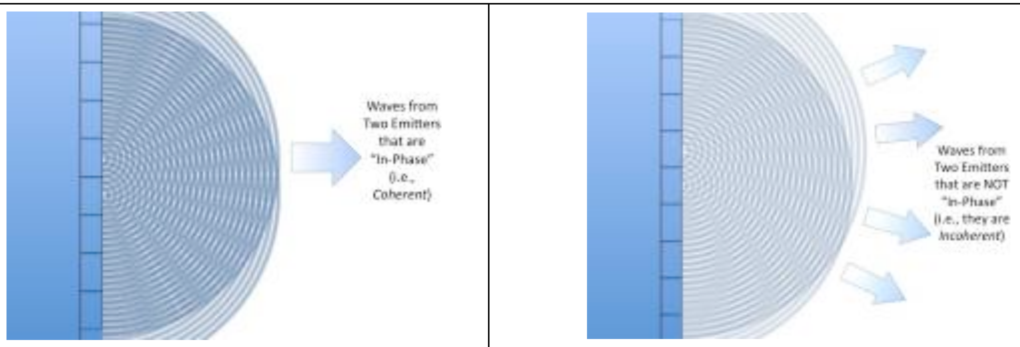
The term “diffraction-limited optics” may sound difficult to understand, but it really isn’t. EM waves are involved in numerous common phenomena, such as the beam from a flashlight, radio transmissions, and microwave ovens. The first time that one drives in the fog at night or shines a flashlight into a mist, the problem is obvious: beams of light (and indeed all EM waves) spread out with distance. Even with a large mirror like the kind found in a commercial spotlight, it’s easy to see the light spreading out the further it goes into the sky. The principal ways to improve this situation are (1) to make the aperture larger (like the reflector in a spotlight versus that in a flashlight), or (2) to create the EM waves so that they are *coherent* – which is to say, so that all of the waves are “in phase” (i.e., in lockstep with one another). Figure 4-1 illustrates the difference between coherent and incoherent EM waves. As illustrated, when a number of EM emitters are all in phase, the waves combine to support one another (called “constructive interference”); when they are out of phase, they counter one another where the peak of one wave meets the low point of another (naturally enough, called “destructive interference”).

However, even coherent EM waves spread out – whether they are radio waves or light from a laser. If the emitted energy has a particular shape – known as a “Gaussian distribution” – across the face of the transmitter, then the spread of the coherent EM waves is as small as physically possible and is known as “diffraction limited.” It may be described by the equation in Figure 4-2; the figure also illustrates the relationships among the four critical parameters in diffraction-limited optics: (1) the wavelength of a coherent EM beam, “l_{Beam},” (2) the diameter of the transmitter, “D_{Xmitter},” (3) the distance over which the beam travels, “Separation$_{\text{Xmitter-to-Rcvr}}$,” and, (4) the optimum diameter of the receiver, “D_{Rcvr},” where the EM beam ends.

Figure 4-1 Coherent vs. Incoherent EM Waves

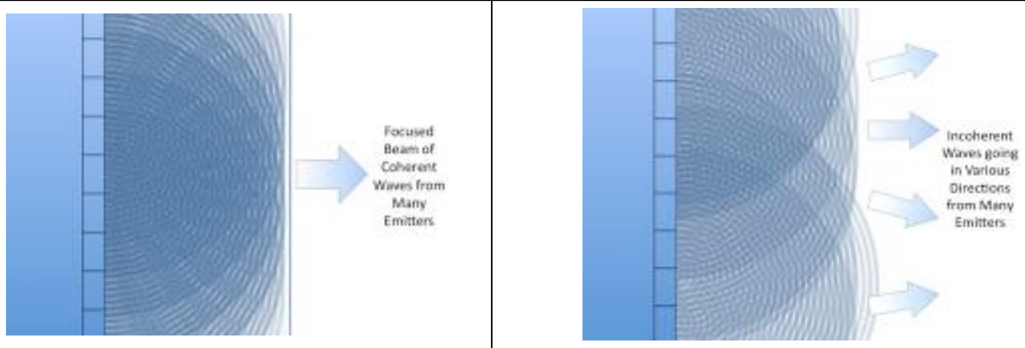


Regular Waves from a Single Emitter



Two Emitters, Which are in Phase (Coherent)

Two Emitters, Which are NOT in Phase (Incoherent)



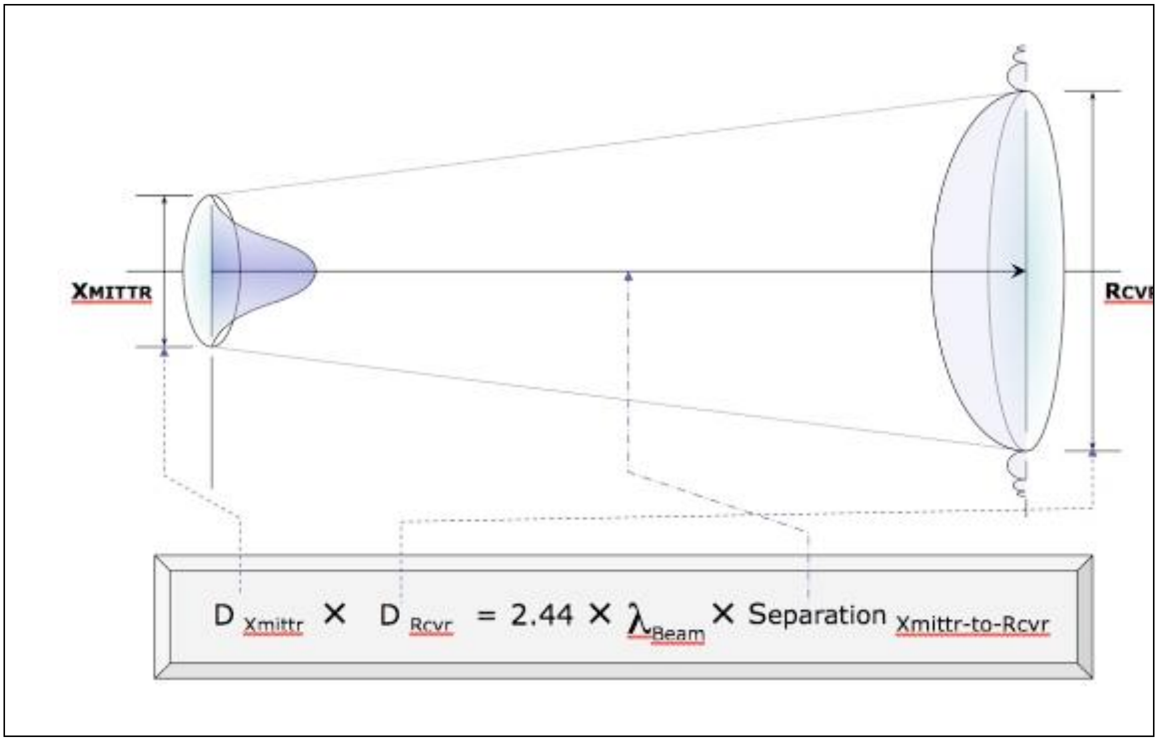
Coherent Waves from Many Emitters Cooperating to form a Beam, and Spreading out Much more Slowly

Incoherent Waves from Many Emitters Spreading Out Rapidly in Many Directions

Credit: Artemis Innovation Management Solutions LLC (2013)

Of course, not all of the energy that is transmitted falls into what is called the "main lobe" in the center of the received transmission. [2,3] As Figure 4-2 shows, a small amount of the transmitted power falls outside the *main lobe*, and into what are called "side lobes". (Note that in the figure, only a cross-section of each of the *side lobes* is shown; the actual *side lobes* are rings of EM energy that circle the *main lobe* at increasing distance and decreasing energy in each ring.)

Figure 4-2 Transmitter / Receiver Scaling Relationships



Credit: Artemis Innovation Management Solutions LLC (2010)

One more thing… Another detail concerning the optics should be mentioned because it directly affects how a WPT system would operate. The various emitting elements of the transmitter (as shown in Figure 4-2) <u>must</u> be physically close to one another (i.e., separated by less than ½-wavelength). If they are separated from one another by more than this – in what is called in antenna design a "sparse array" – then depending on the amount of separation a substantial fraction of the transmitted energy will be dumped outside of "main lobe" circle that defines the receiver (D_{Rcvr}) into what are called “grating lobes,” a special type of side lobe. There is no way around this phenomenon, which is fundamental to the physics for coherent EM waves: the greater the separation between the emitting elements, the more energy will be lost.

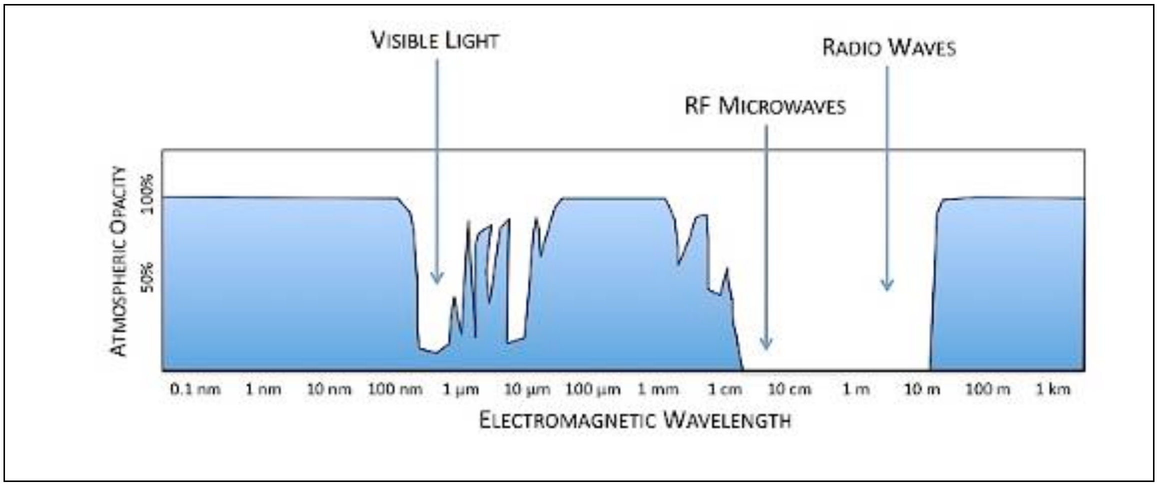
In summary, to transmit power over long distances, EM waves must be coherent and the aperture of the transmitter must be large relative to the wavelength; for a given WPT wavelength and a given distance between the two, the size of the transmitter determines the size of the receiver. And, the emitting elements must be close to one another – otherwise energy will be lost.

There is one more extremely important physical constraint upon SPS concepts and on wireless power transmission: the character of Earth’s atmosphere.

The Opaqueness of Earth’s Atmosphere

We don’t normally think of Earth’s atmosphere as being opaque; after all, we can see right through it (at least at short range). However, a foundation for SPS system design choices – including the selection of wireless power transmission technologies to be used – includes careful consideration of the transparency of Earth’s atmosphere to different portions of the electromagnetic (EM) spectrum. Figure 4-3 illustrates the attenuation of EM waves through the atmosphere, for various wavelengths.

Figure 4-3 Atmospheric Attenuation of EM Energy at Various Wavelengths



Credit: Artemis Innovation Management Solutions LLC

As shown in the figure, Earth's atmosphere is largely opaque to EM waves; however, there are several "windows" – specific wavelengths at which the atmosphere is essentially transparent. For example, Earth's atmosphere is largely but not completely transparent at wavelengths near those of visible light. (If this were not the case, life as we know it on Earth would be impossible…!) However, for WPT applications, there are obvious additional issues associated with atmospheric water vapor and weather (fog, clouds, haze, etc.). The atmosphere is also transparent across a wide range of radio frequency (RF) wavelengths, between 1 centimeter and 10 meters. Figure 4-4 is a close-up on the atmospheric window for radio frequency (RF) EM energy, from around 0.3 to 30 centimeters in wavelength.

Figure 4-4 Atmospheric Attenuation of RF at Various Wavelengths

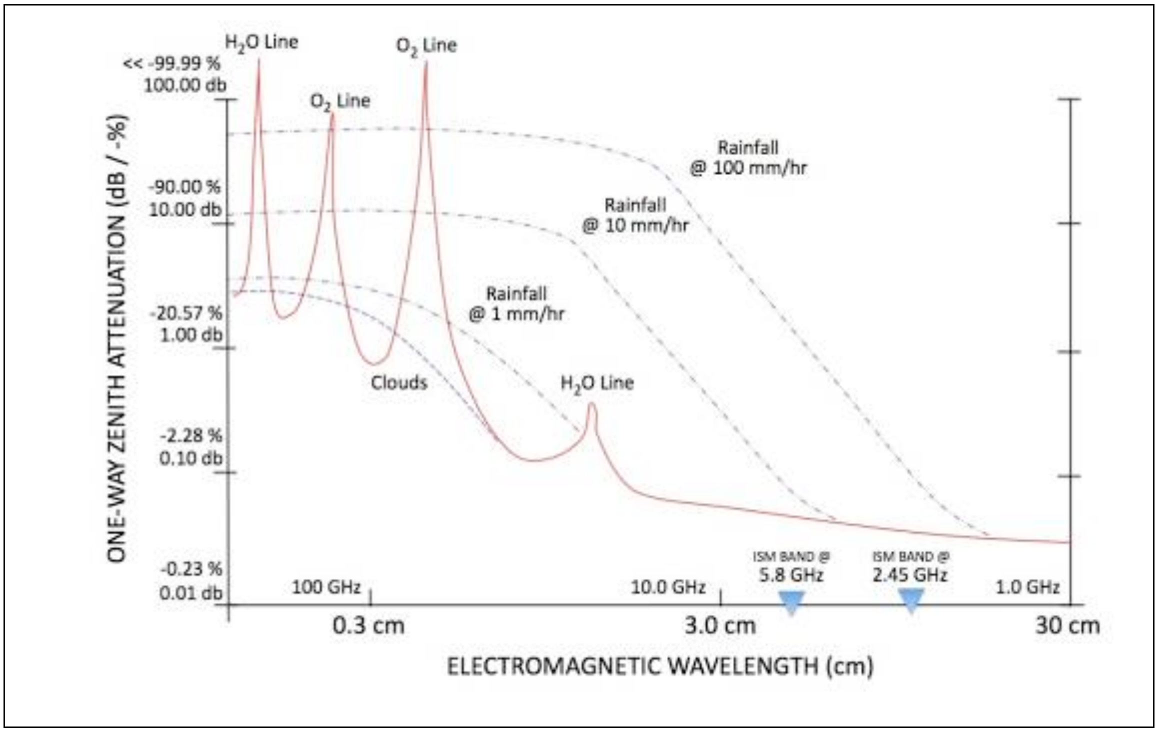


Figure Credit: Artemis Innovation Management Solutions, 2013, after NASA Ref. Pub. 1082(04), Feb. 1989

Frequencies between 2 GHz to 10 GHz – in the range known as microwave radiofrequencies – represent highly promising candidates for SPS wireless power transmission.[4] As Figures 4-3 and 4-4 indicate, at lower wavelengths (i.e., higher frequencies), atmospheric and/or weather-related attenuation increases drastically. For example, the attenuation at 10 GHz or less is about 1% while the attenuation at 100 GHz or greater is roughly 20% or more. You will also see that two specific wavelengths are highlighted in the figure; there is a reason.

Use of the electromagnetic spectrum (particularly, the RF) is managed by an organization known as the International Telecommunications Union (ITU) through a series of working groups focused on specific scientific and engineering issues. Several frequencies are reserved for non-communications applications; these are known as the Industrial, Scientific, and Medical (ISM) bands. Two of these ISM bands are of particular interest in prospective SPS and WPT applications: 2.45 GHz and 5.8 GHz. These are highlight in the figure. These two frequencies fall exactly within the range where the atmospheric attenuation of EM energy is the least (The regulatory aspects of this topic are discussed in Chapter 9).

In the case of a laser power transmission approach, the typical frequency of interest is in the near-Infrared (near-IR) portion of the spectrum, with a wavelength of approximately 0.00000098 meters [or roughly 980 nanometers (nm), corresponding to a frequency of 306,122 GHz]. Recall that the physics illustrated in Figure 4-3 and discussed above applies equally to microwave and to laser WPT optical systems. Regarding the laser, the transmitter and receiver diameters can be made considerably smaller than the RF cases. However, there will be significant interactions (absorption) by the air, by water vapor, and increasingly by weather phenomena such as cloud cover or storms due to water droplets in the air.

An important policy and safety-related consideration for wireless power transmission systems – especially for laser concepts, but also for RF – is the issue of maximum beam intensity at the receiver. (This topic is discussed in Chapter 10, which concerns health, safety and environmental concerns.)

Solar Intensity at Earth

Another unavoidable constraint placed by nature on would-be SPS designers is the intensity of sunlight. The maximum intensity of sunlight on Earth is about 1,000 watts per square meter (W/m^2), observed only at noon on a clear day at the Equator. In most locations on Earth, however, the maximum solar intensity is less – about 800 W/m^2. However, in space at the distance of Earth's orbit around the Sun, the average intensity of sunlight is about one-third higher, or about 1,361 W/m^2.

What this means for SPS is straightforward, just as it is for conventional ground-based solar power systems: in order to generate a large amount of power, the system must intercept and convert sunlight across a very large area. For example, to generate 1 MW of power, an appropriate solar array with a conversion efficiency of about 30 percent (a good value) must, in most locations on Earth and at noon, intercept sunlight across an area of about 4167 m^2 – equivalent to a circle with a diameter of some 72 meters. To generate the same 1 MW of power, an appropriate solar array in Earth orbit (again with a conversion efficiency of about 30 percent) would have to intercept sunlight across an area of about 2,450 m^2 – equivalent to a circle with a diameter of a bit less than 56 meters. In order to produce 1,000 MW (power equivalent to a nuclear power station), the solar array would have to be one thousand times larger in area than in the 1 MW case. (You may recall Chapter 1 discussed the differences in space-based versus ground-based solar in terms of area requirements and variations in sunlight intensity over time.)

In summary, what this means is that solar power systems – in space or on Earth – must be large in order to generate meaningful amounts of power.

Heat Rejection

Another physical constraint on Space Solar Power may be found in the fact that in electronics *nothing is perfect*. When electrical equipment operates, a fair amount of the energy does what it is intended to do – whether it is routing Internet traffic or roasting a chicken – however, some fraction is lost due to inevitable inefficiencies that occur in all systems. This electricity becomes "waste heat" that must be radiated away or otherwise dispersed into the local environment. For example, when less than perfect computer systems on Earth operate and energy is wasted, the solution is usually to let convective cooling by the air take away most of the heat; this is the reason why personal computers have built-in fans – to keep them cool.

In an SPS, at a minimum when sunlight is converted into electricity (or otherwise converted), there is leftover energy and when the electricity is converted into the coherent EM transmission, again there is leftover energy. However, in the vacuum of space it is impossible to use fans to cool the equipment. That "leftover" energy must be radiated out into space – like the heat from a hot oven radiates out into a kitchen when the oven door is opened.

In this case, the physics of the radiated power of the waste heat occurs according to an equation known as the *Stefan-Boltzman Law*; in particular:

$$\text{Power Radiated} = A * \quad * S_{SB} * T^4$$

In this equation, A is the area from which heat is being radiated,   is the emissivity of the surface (i.e., it's inherent ability to radiate electromagnetic energy), S_{SB} is the Stefan-Boltzman constant (i.e., $S_{SB} = 5.6704 \times 10^{-8}\ J\ s^{-1}\ m^{-2}\ K^{-4}$), and T is the absolute temperature of the surface (in degrees-Kelvin).[5]

What this means is that for any SPS concept, because the electrical component technologies will *never* have perfect efficiency, temperatures must increase to the point at which the wasted energy – the *waste heat* – can be rejected into space. Since the amount of heat radiated varies as the fourth-power of the temperature, increasing the waste heat by a factor of sixteen only results in an increase in the temperature of a factor two (since $2^4 = 16$).

In summary, any SPS design must take into account the fundamentals of thermal management. Large surfaces, efficient and/or lightweight radiators, high-efficiency devices, etc., will all be important.

Placement in Space

A final physical constraint on SPS design choices is found in the velocity of different locations in space relative to the surface of Earth. The 24-hour day corresponds – as Galileo pointed out a little more than 400 years ago – to the rate at which our planet rotates on its axis. In order to stay in a low Earth orbit (LEO) in a range from roughly 200 to 2,000 km overhead, a satellite must move at a velocity of 7 to 8 km per second (about 15,400 mph to 17,400 mph), circling the world every 90 to 130 minutes. So, a satellite in LEO travels around the world 12 to 18 times every 24-hour day. As a result, it would not be possible for an SPS in LEO to constantly send energy to a particular receiver on Earth. In fact, SPS concepts based in LEO have an issue having to do with utilization of fixed capacity: most of the time they cannot deliver power to anyone because the SPS will be over water (since 75% of Earth's surface is ocean). They have another problem, which is initial cost: in order to best use the capacity of a single SPS in LEO, multiple ground receivers should be built. (This problem becomes less important in the event of a constellation of SPS serving a large number of receivers.)

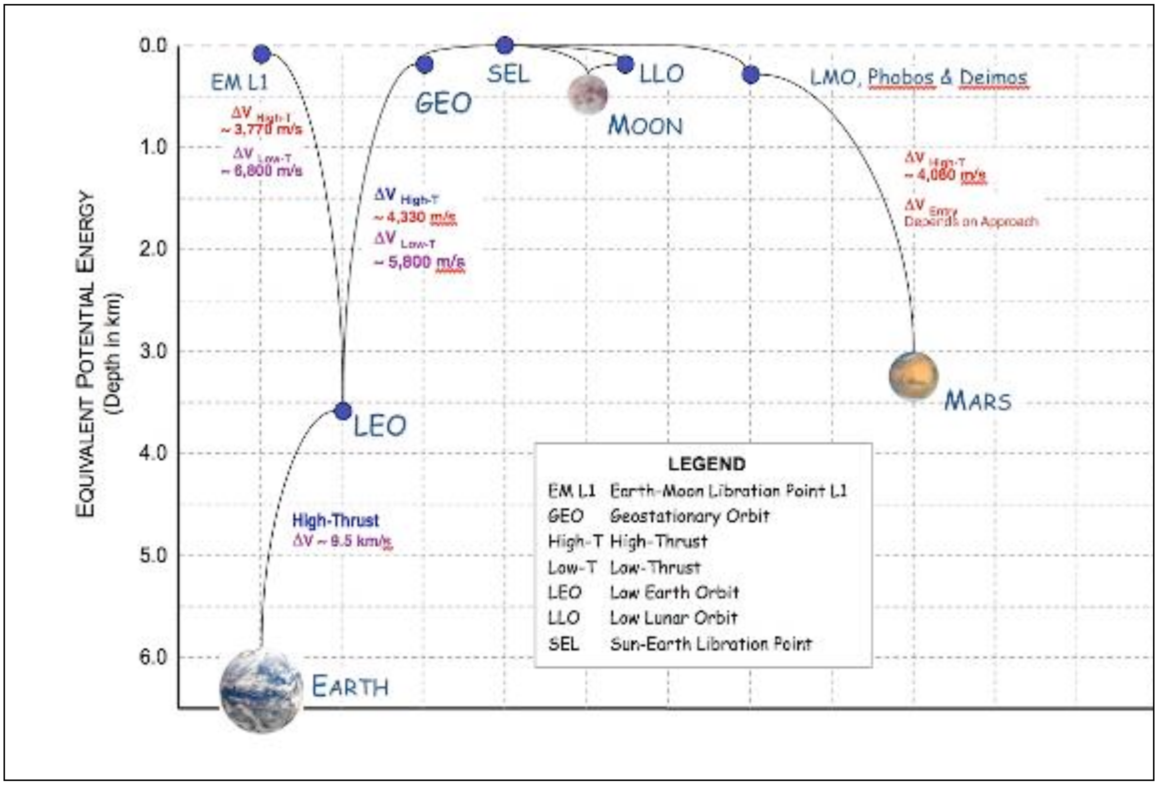
As one looks at higher altitudes (above LEO), there is a particular orbit – a circular orbit at 35,786 kilometers (i.e., some 22,236 miles) – that has the special property that a satellite in this orbit travels around Earth exactly once every 24 hours. If the satellite is in an orbit directly above the equator, it appears to remain fixed in the sky overhead for an observer on Earth; this is the location mentioned previously known as geostationary Earth orbit (GEO). If the satellite's orbit is inclined somewhat from the equator, then it appears to move in a figure-8 pattern in the sky (with the center point of the figure-8 staying fixed overhead). Further away from Earth than GEO, it orbits more slowly than once every 24 hours, and again the SPS will move in the sky relative to receivers on Earth. For example, the Moon – at a distance of some 384,400 km (or 238,900 miles) from Earth – orbits approximately once every 28 days.

So, the **unique** location in space where an SPS can be placed such that it will always be directly above the same receiver on the ground – or a set of receivers any of which might be used at a given time – is in geosynchronous Earth orbit (GSO), with a geostationary orbit above the equator (GEO) the most desirable.

However, the fact that GSO and GEO are geometrically preferred for continuous power transmission has consequences for supporting space transportation systems as well as for the SPS itself: it requires a great deal of energy and more complex equipment to transport SPS systems from Earth to GEO. Figure 4-5 illustrates the transportation problem in terms of the energy required to reach LEO, GEO, the Moon, and other destinations. As shown, moving a single kilogram (~ 2.2 lbs) from Earth to LEO requires roughly 12 kilowatt-hours of energy (roughly 43MJ); similarly, transporting that kilogram from LEO to GEO requires another 4-6 kWh. As a result, deploying an SPS with a mass of 10,000 MT to GEO (i.e., 10,000,000 kg) will require about 200,000,000 kWh! Fortunately, through the use of Solar Electric Propulsion (SEP), the great majority of the energy required to move the SPS from LEO to GEO may be generated from sunlight in space.

Also and surprisingly, it does not take an efficient SPS very long to "pay off" the energy indebtedness that may be incurred by deployment. As discussed later, a 10,000 MT platform should be capable of almost continuously delivering some 1,000 MW of power or more, or about 24,000,000 kWh per day. As a result, such an SPS would require less than two weeks to repay the energy necessary to transport hardware to LEO and on to GEO. Of course, in addition to the platform hardware, it is necessary to launch propellant to transport the SPS pieces from LEO to GEO as well as for platform maneuvers in space. At any in-space transportation systems moment, a reasonable estimate of the total energy payback time may be obtained by doubling the initial number and then doubling it again (i.e., delivering one kg of SPS to GEO would require roughly 48 kilowatt-hours or energy). Even so, that only translates into an energy payback time of about eight weeks for an SPS. (Stated differently, it should require only about 8 weeks for a large SPS to deliver to Earth an amount of energy equivalent to the energy cost to transport the system from Earth to GEO.)

Figure 4-5 Energy Requirements for Transportation from Earth to Targets of Interest



Credit: Artemis Innovation Management Solutions LLC (2013)

Despite this, it is clear that because of the energy required, and especially the cost of space transportation, the deployment to GEO implies that SPS concepts should be as low in mass as possible. There is another solution to this problem that might almost entirely avoid the need to make SPS platforms lightweight: the use of extraterrestrial resources as the source for satellite logistics – e.g., propellants and hardware. (These topics are discussed in Chapter 7.)

Summary of Important Physical Constraints

The important external physical constraints on SPS designs include: (1) the optics of wireless power transmission; (2) the character (i.e., the opacity) of Earth's atmosphere; (3) the intensity of sunlight at Earth; (4) the need to remove waste heat from the satellite; and, (5) the location of the system in space.

Now, before reviewing various examples of SPS architectures, let's look at SSP engineering and technology-related issues.

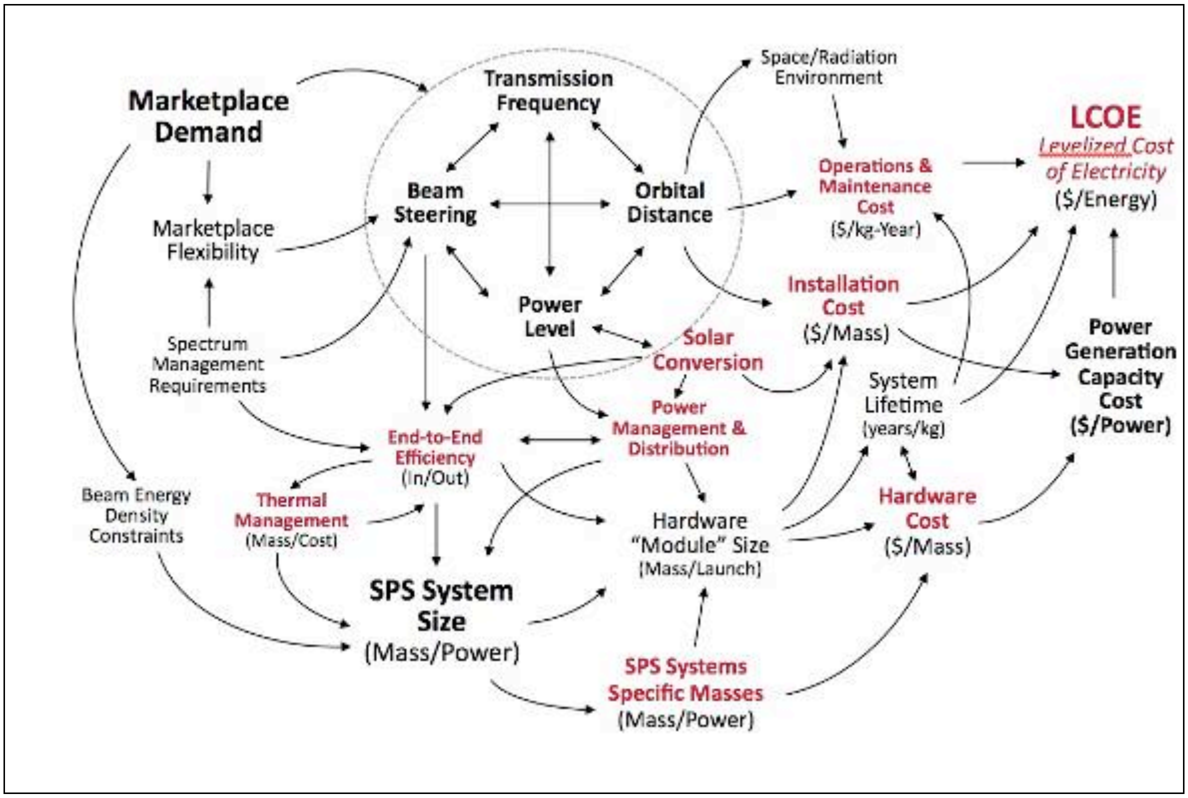
Engineering and Technology Considerations

Like any major energy system, solar power satellites will involve considerable complexity; there are numerous engineering issues based on the availability of different technologies and the interactions among them. Figure 4-7 illustrates this spider's web of complex interrelationships among SPS system characteristics and physical parameters that must be incorporated into any detailed end-to-end systems analysis of various markets, technologies, and systems architectures for solar power satellite options.

For example, the overall level of "marketplace demand" (in the upper left of the Figure) sets the context for the flexibility that the system should provide to meet that demand, as well as the cluster of functional characteristics concerning the Wireless Power Transmission (WPT) system: power level, beam steering, the frequency of the WPT transmission, and the distance between the SPS in its orbit and the receiver(s) on Earth. Similarly, and at the opposite end of the "web," the levelized cost of electricity (LCOE) at which the system can deliver energy ($/kWh) is driven by the costs of operations and maintenance (O&M) and the initial cost of the power generation and delivery systems ($/watt), including both the on-ground and in-space hardware cost and the cost to install the system elements, and so on.

These parameters change depending on the details of the SPS system architecture option being considered; for example, a microwave power transmission system may very well have characteristics that differ greatly from those of a laser power transmission system. The discussion of these engineering characteristics – including the pros and cons of each – must be deferred until later in this chapter when specific SPS concepts are introduced and evaluated.

Figure 4-7 Network of Solar Power Satellite Systems-Technology-Market Relationships

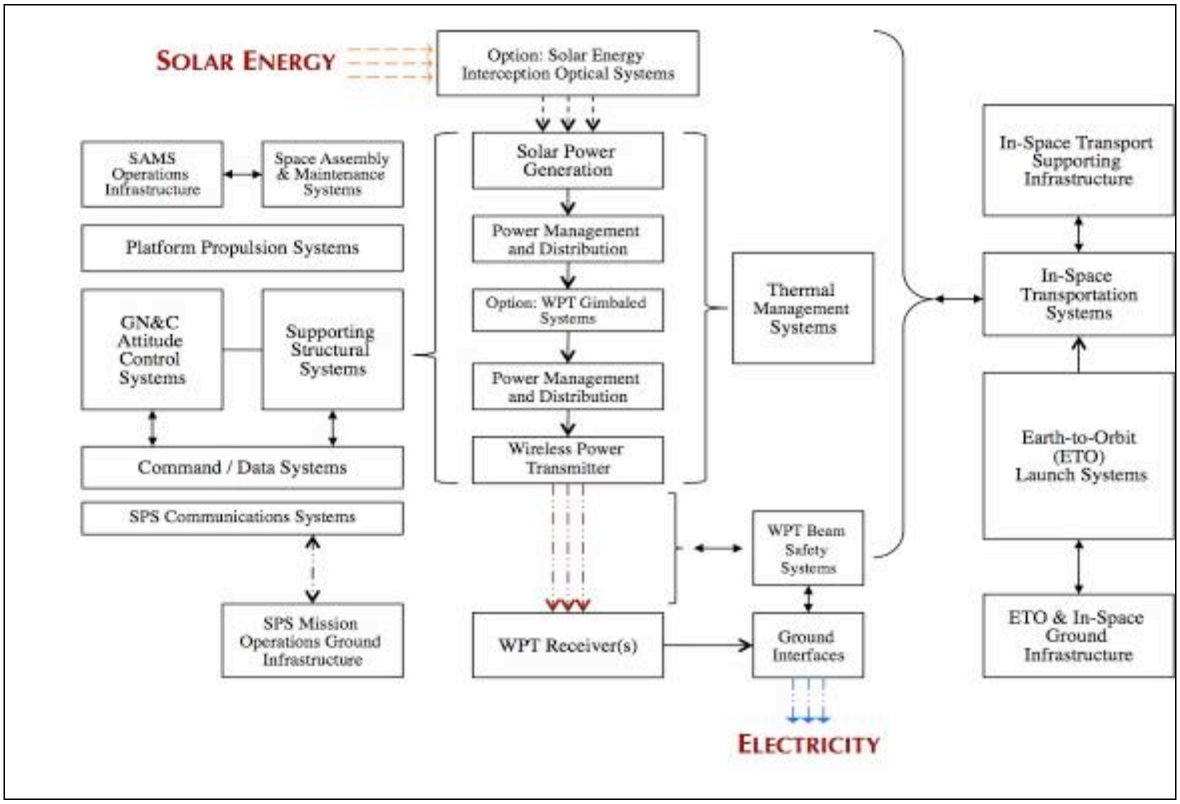


Credit: Artemis Innovation Management Solutions LLC (2013)

Another way of looking at SPS is in terms of the common functions that must be accomplished, regardless of the details of the systems concept. Figure 4-8 presents such a view, laid out in a block diagram in terms of the major functional areas to be accomplished. Please note, however, that this diagram is valid for the great majority of, but not all, approaches to delivering solar power from space to Earth; for example, this diagram does not include the various functional areas that would be required to implement Lunar surface-based Solar Power (LSP), discussed as follows.

The central point to take away from both of these diagrams is this: SSP is a complex, interconnected engineering challenge. Optimizing one characteristic (e.g., making the transmitter smaller) may ruin another (i.e., end-to-end efficiency). Not surprisingly, defining an SPS concept requires a thoughtful consideration of multiple variables simultaneously. As mentioned before, there are a great number of different possible approaches to the SPS challenge. For example, NASA’s Fresh Look Study of Space Solar Power in the mid-1990s documented more than 30 different ways to deliver solar power from space to Earth, or to distribute energy on Earth through space. How, then, to organize our discussion of various SPS options?

Figure 4-8 Functional Block Diagram of a Generic Solar Power Satellite Architecture



Credit: Artemis Innovation Management Solutions LLC (2013)

An examination of Figure 4-8 suggests several key points that discriminate between differing broad families of SPS architecture types. The type of wireless power transmission systems is a clear point of demarcation. Similarly, the existence – or absence – of electrical interconnects that are gimbaled (i.e., rotating) between the Earth-pointing WPT transmitter and the Sun-pointing solar power generation (SPG) system is another.

There is a third choice: centralized versus distributed Power management and distribution (PMAD). And, lastly, another choice that is not reflected in the generic functional breakdown structure is the following question: is the architecture monolithic or modular? In other words, to what degree does the SPS platform comprise many identical "piece parts" versus a single large system? These engineering design choices establish a useful basis for categorizing SPS concepts.

SPS System Options: Considering the…Possibilities

In the preceding paragraphs, we reviewed first the physical constraints on Space Solar Power and then the engineering and technology related issues that must be considered. Lastly, we examined a generic breakdown of the functions that (almost) any SPS must perform to deliver solar energy harvested in space to markets on Earth. Based on these considerations, the following are four different major functional questions that may be posed:

- What type of type of wireless power transmission will be used?
  - In other words: microwave, millimeter-wave or laser?
- Does the SPS use electrical power management and distribution or reflectors to link the Sun-pointing portion of the platform to the Earth-pointing portion?
  - In other words: does the platform require low voltage local PMAD, or higher voltage long-distance PMAD?
- Is the SPS monolithic or modular?
  - In other words: is the platform a single large system, or does it comprise many individually identical system elements?
- Does the SPS use large platform scale or local scale gimballed systems as “interconnects?”
  - In other words, does the platform use electrical wiring across a rotating interface to connect sun-pointing PV arrays to Earth-pointed WPT transmitters?

The discussion that follows looks in brief at some sixteen different SSP system architecture options. On the second page following, Table 4-1 presents this set of sixteen different architectures, organized into six different types of Solar Power Satellites, plus a catchall category of miscellaneous types; these are organized according to these four major functional questions, plus several additional characteristics.

Table 4-1 Trade Space of SPS Concept Options

	Wireless Power Transmission	Sun-vs-Earth Pointing Link	Modularity	Gimbaling
Type I	Microwave	PMAD	Monolithic	Platform-Level
1979 SPS Reference	Microwave	PMAD	Monolithic	Platform-Level
Solar Disc	Microwave	PMAD	Monolithic	Platform-Level
Type II	Microwave	Reflector	Monolithic (Part)	Platform-Level
Abacus Reflector	Microwave	WPT Reflector	Monolithic (Part)	Platform-Level
Integrated Symmetrical Concentrator (ISC)	Microwave	Reflectors	Monolithic (Part)	Platform-Level
Type III	Microwave	PMAD	Modular	
SunTower/SailTower	Microwave	PMAD	Modular	Array / None
Type IV	Microwave	Reflector	Hyper-Modular	Platform-Level
Standard Sandwich SPS	Microwave	Reflectors	Hyper-Modular	Platform-Level
Modular Symmetrical Sandwich	Microwave	Reflectors	Hyper-Modular	Platform-Level
Type V	Microwave	Reflector	Hyper-Modular	local
SPS-ALPHA	3-Axis / Gravity Gradient	Reflector	Hyper-Modular	local
Type VI	High-Frequency	Variable	Variable	Variable
Modular Laser	Near-Visible Laser/Optics	PMAD	Modular	local
mm-Wave / Laser SPS with Relay	mm-Wave / Laser and Optics	PMAD	Modular	Platform-Level
Solar-Pumped Laser	Near-Visible Laser/Optics	Optics	Monolithic	Platform-Level
Others	Variable	Variable	Variable	Variable
Lunar Solar Power	Microwave	PMAD	Modular	None
Libration Point SPS	Microwave	PMAD	Modular	None
Space-Based Mirror	Sun Light	Reflectors	Monolithic	None
Microwave Swarm	Microwave	PMAD	Hyper-Modular	None
Demo Concepts	Variable	Variable	Variable	Variable

Table 4-1 (continued…)

Concentration	**Attitude Control**	**Location**	**In-Space Infrastructure**	**Additional Notes and/or Features**
None	3-Axis	GEO	Factory in Space	HLLV RLV/TSTO
None	Spin	GEO	Robotic SAMS	Thin-Film PV
None	3-Axis	GEO	Robotic SAMS	RF Reflector “PERFECTLY” FLAT
Platform	3-Axis / Gravity Gradient	GEO	Robotic SAMS	Thermal Management Issues
Array / None	Gravity Gradient	LEO / GEO	Robotic SAMS	Multiple Receivers required for LEO Option
None	Gravity Gradient	GEO	Robotic SAMS	Several WPT Options
Array Level	3-Axis / Gravity Gradient	GEO	Robotic / Self-Assembly	Thermal Management Issues
Platform & Array Level	3-Axis / Gravity Gradient	GEO	Self-SAMS	Various Configurations
Array Level	3-Axis	GEO	Robotic / Self-Assembly	Relay Option
Variable	3-Axis	GEO	Robotic / Self-Assembly	High-Altitude Relay @ Earth
None	3-Axis	GEO	Robotic / Self-Assembly	Relay Option
None	N/A	Lunar Surface	ISRU & Factory on Moon	Earth Orbit Relays Required
None	3-Axis	Sun-Earth L1	Robotic SAMS	1.5 M km Distance
None	3-Axis	GEO	Robotic SAMS	Optical Reflector “PERFECTLY” FLAT

None	3-Axis	LEO/MEO/GEO	N/A	Station-Keeping Issues
None	*Variable*	*Variable*	*Variable*	*Variable*

Type I SPS Concepts[6]

Microwave WPT Systems; Electrical PMAD Interconnects; Monolithic Architecture; and Large, Platform-Level Gimbaled Systems

The SPS system developed by the 1970s joint DOE-NASA study as described in Chapter 3 epitomizes **Type I** SPS system concepts. This family of options involves WPT at microwave RF frequencies, electrical interconnections between sun-pointing and Earth-pointing portions of the platform, centralized power management and distribution across the SPS, and monolithic system architectures. The paragraphs that follow describe two different **Type I** SPS concepts, including the 1979 SPS Reference System and the Solar Disc SPS concept developed during the SERT program. Table 4-1 summarizes some aspects of a **Type I** SPS.

The 1979 SPS Reference and Related Concepts

The 1979 SPS Reference System (see Figure 4-9) comprises a number of major system elements within an overall architecture that resembles an extremely large but otherwise conventional spacecraft of the 1960s-1970s.

Figure 4-9 Diagram of the Key Elements of the 1979 SPS Reference

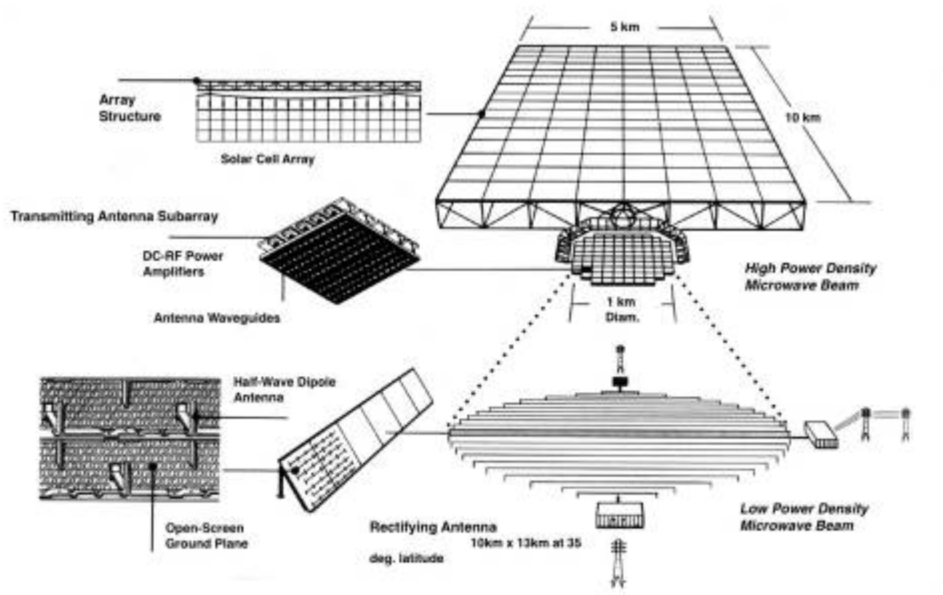


Image Credit: US Government Studies (c. 1980).

It includes a large sun-pointing conventional solar array mounted on an in-space assembled structural truss system; a rigid, Earth-pointing WPT waveguide structure onto which RF amplifiers (base-lined as large electron tube devices, such as Klystrons) are attached. Also, there is a large, high-voltage rotating connector between the solar array and the WPT system.

All of these elements were to be assembled into a single, monolithic spacecraft platform – rather like a tremendously large conventional spacecraft. There are a number of variations on the detailed configuration of the 1979 SPS Reference

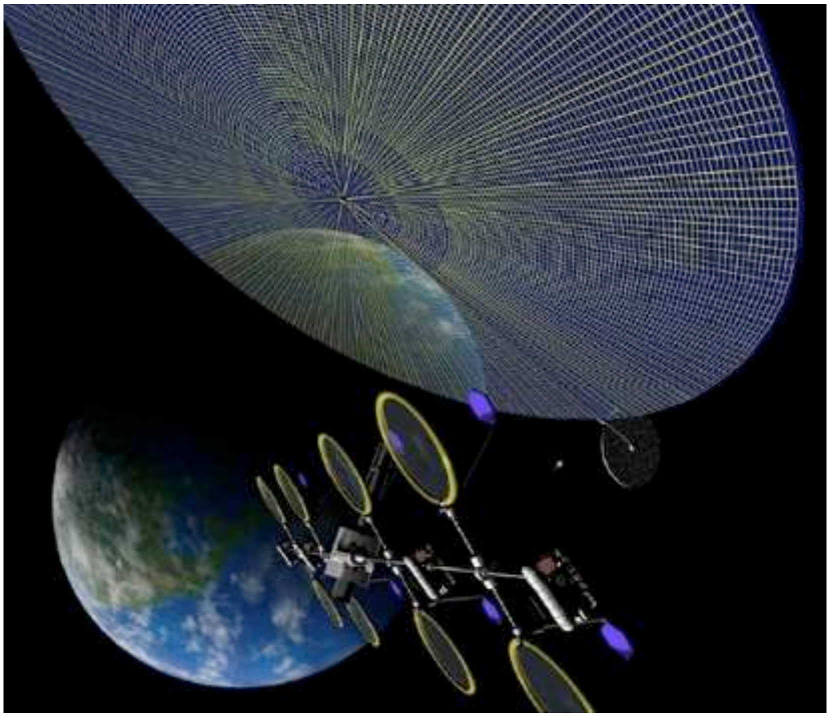
System as shown in Figure 4-9, including a version with double the solar area (i.e., 20 km by 5 km) and a transmitter on each end and a version with trough-style concentrators on the PV array. As discussed in Chapter 3, this architecture requires an extensive and unique ETO launch capability as well as a large-scale in-space infrastructure comprising in-space factories in LEO and GEO.

Solar Disc SPS

The “Solar Disc” Space Solar Power concept involves an extensively axi-symmetric, primarily monolithic, space segment (with highly modular components) that ‘grows’ in geostationary Earth orbit (GEO), and can provide early ‘on-line’ capability at a reduced power level. Figure 4-10 presents a visualization of the Solar Disc solar power satellite concept.

The “Solar Disc” concept is a single, large-scale GEO-based, RF transmitting space solar power systems. A single satellite/ground receiver ‘pair’ would be used where this pair could be sized according to the specific market, ranging from approximately 1 GW to 10 GW scale. Each satellite resembles a large disc approximately 3-to-6 kilometers in diameter. This disc is continually Sun pointing, with a hub occupying the center; the hub integrates power generated by each segment of the PV disc. This power is conveyed via two redundant structures (like the fork on the front wheel of a bicycle) to a continually Earth-pointing phased array that is approximately 1 kilometer in diameter. When defined, the concept was assumed to transmit at 5.8 GHz at a transmitted power level of 2-8 GW. Total beam-steering capability is 10 degrees (±5 degrees). The transmitter array is an ‘element-and-subassembly-tiled’ plane that is essentially circular, about 1000 meters in total diameter, and approximately 1.5-to-3.0 meters in thickness.

Figure 4-10 Solar Disk Rotating Thin Film PV SPS Concept Based in GEO



Credit: NASA Artwork, by P. Rawlings / SAIC c. 1997

This concept involved a high level of modularity at the component level, but required large-scale systems for key functional elements including: (1) the power management and distribution system across the back of the transmitter; (2) the rotary PMAD coupling at the back of the transmitter; (3) the hub of the rotating system (the "wheel" in the figure); and (4) the power cables (and supporting structure) from the hub of the "wheel" to the back of the transmitter. As a result, no concept-unique ground launch infrastructure or ETO launch systems are required beyond those necessary to achieve low launch costs (on the order of $500 per kilogram).

Sunlight-to-electrical power conversion would be via thin-film PV array. This system is anticipated to be largely modular at the sub-element level and deployable in "units" that represent individual concentric rings. The collection system is intended to be always Sun facing (with orientation by angular momentum). Given the typically lower efficiency of such PV cells, the rotating disc would be large – perhaps as much as five or more kilometers in diameter. Heat rejection for power conversion and conditioning systems were assumed to be passive, but where active cooling is needed, the goal would be for it to be modular and integrated with power transmission systems.

Assessment of Type I Concepts

There have been numerous advances in relevant subsystem technologies that are appropriate for SPS concepts of the 1979 Reference System type. The most significant advantage is the potential to incorporate exceptionally low specific mass, thin-film PV arrays in the platform. Also, in this SPS type, most major technologies may be independently developed up to an intermediate level of maturity (e.g., a "Technology Readiness Level" of TRL 3) and then later integrated (e.g., WPT and SPG are fully separated). Systems-level demonstrations of those technologies would be much more challenging with increasing scale, however, due to the higher levels of integration required.[7]

There are a number of inherent technical hurdles that must be overcome in this case. For example, in order to take best advantage of low mass PV, advanced technologies for PMAD systems would be needed, such as very high voltages, or high-temperature superconductor (HTS) systems. In addition, for an operational system the "cost to first power" is likely to be higher than for other SPS types due to the very substantial fixed infrastructure requirements – including, but not limited to the need for larger, specially developed ETO systems, large-scale LEO infrastructure and extensive GEO in-space assembly and construction (ISAAC) infrastructure.

The weaknesses of this family of concepts are really three-fold. First and foremost, these concepts were 'stick-built' – meaning that the specific pieces of the platform were launched individually, were "dumb," and were entirely dependent on large-scale in-space infrastructure for in-space assembly and construction. Secondly, because the concepts of the 1970s involved the use of conventional materials in solar cells and in structures, achieving relatively low mass depended on the assumption of extremely high voltages. The solar arrays in the Reference System were assumed to operate between 10,000-50,000 volts for this reason. (This is roughly 1,000-times greater than the voltage used in a conventional communications satellite.) Thus, the concepts involved significant risks that the system would 'short-out' when it experienced the first, entirely inevitable micrometeorite impact.

In the 1970s, the efficiency of microwave solid-state devices was still hovering in the range of 30-40 percent. As a result, the technology assumed for power beaming involved electron tubes (large ones, such as klystrons, or perhaps smaller ones, such as magnetrons). The microwave energy from these tubes were to be passed through a complex series of metal pipes – waveguides – and transmitted ultimately toward Earth from an enormous, almost perfectly flat transmitting antenna 1,000 meters (more than half a mile) in diameter, which required mechanical pointing at targets on the Earth.

Finally, a remaining weakness of the 1979 SPS Reference System and related concepts was that it required the creation of a very large-scale, reusable launch vehicle system. This heavy lift launch vehicle (HLLV) system relied on a two-stage-to-orbit (TSTO) approach and was planned to launch approximately 250 MT of payload into a low Earth orbit. The gross liftoff weight (GLOW) of these systems was estimated to be as high as 11,000 MT. The facilities required to support these enormous HLLVs were extremely large as well and entailed extensive operations and maintenance (O&M). Nevertheless, the ETO cost per kilogram of payload for these launch systems was projected at an exceptionally – and almost certainly unrealistically – low figure: about $50-$100 per kg. A more credible estimate for the recurring cost per kilogram of payload of a first generation, 99% reusable single-stage-to-orbit (SSTO) vehicle has been estimated to be about $2,000 per kilogram. This challenge might be improved by the Solar Disc approach, but detailed launch requirements are yet to be defined for this architecture. (Launch system concepts and their associated costs are discussed in Chapter 7.)

In order to succeed economically, all of the major system elements of an SPS must be capable of being manufactured drastically less expensively that any current spacecraft or space power system. Can this be achieved? If one is building scores of SPS platforms, the answer can reasonably be expected to be “yes”. However, a central issue for SSP systems concepts is whether or not the first platform can be manufactured cheaply. In the case of the Reference System, the major system elements were – although very aggressive technologically – largely consistent with these goals. Even from the first platform, most system elements were manufactured in extremely large lot sizes (1000’s to 100,000’s of units) and could be expected to be affordable. However, several major system elements were not modular – for example, the unique, 200-300 meter diameter mechanical gimbaled system that connected the phased array to the solar array. Moreover, the systems associated with the in-space infrastructure for SSP system assembly and construction were not planned to be manufactured in anything approaching the quantities envisioned for the platforms themselves. For example, modules for astronauts would have been built in lot sizes of 10's to 20's, extravehicular activity systems in lot sizes of 100's, etc. Hence, although the majority of the mass could be projected to be very low cost ($500-$1,000 per kg), major system elements could be expected to be drastically more expensive (perhaps ($5,000-$20,000 per kg or more).

The general foundations of technology available in the 1970s were vastly inferior to those available today. In computing, avionics, communications, materials, and other areas, the basic technologies of 1976-1980 were vastly behind where they are today, some 40-plus years later. However, several unique technologies needed have not been developed (e.g., the extremely large integrated PMAD system), and are no more mature today than they were then.

Summarizing: **Type I** SPS approaches suffer from a number of significant technical and programmatic challenges, including:

(1) Low maturity for key technologies;

(2) Excessive weight, due in part to huge, high-voltage power management and distribution (PMAD) systems (up to multiple gigawatts at more than 10kV across a gimbaled interface);

(3) Projected up-front development costs for a monolithic platform more than 20 times larger than the International Space Station;

(4) In some instances, the up-front expense of the required fleet of specialized heavy-lift reusable launch vehicles (RLVs); for example two-stage-orbit (TSTO vehicles with payload requirements of up to 250 MT; and

(5) For the 1979 SPS Reference and related concepts, the in-space factories at various orbits, and potentially of enormous scale, see Figure 4-1.

Type II SPS Concepts

Microwave WPT Systems; Reflector-Based Interconnects, Electrical PMAD; Monolithic Architecture; and, Large, Platform-Level Gimbaled Systems

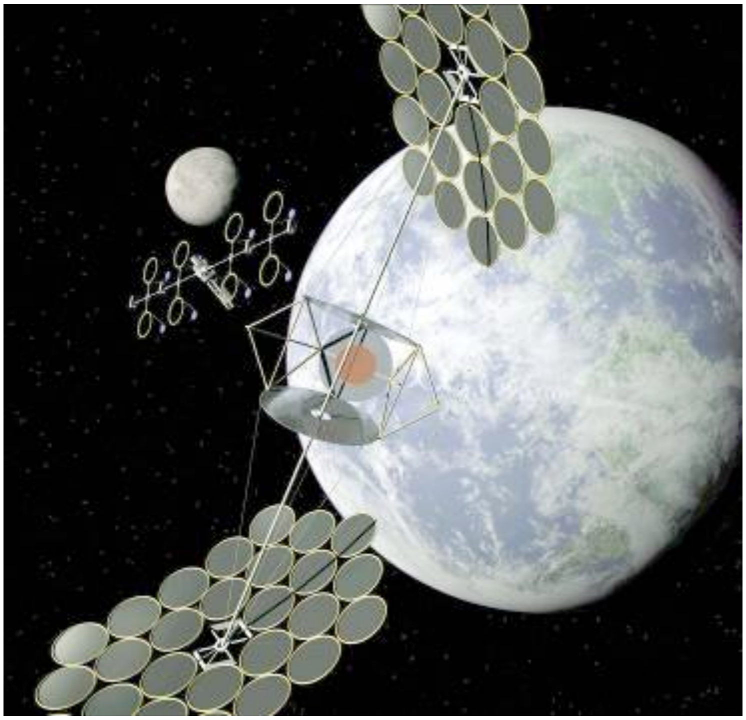
The Integrated Symmetrical Concentrator (ISC), and the Abacus Reflector concepts developed by the NASA SERT program in the late 1990s represent SPS system concepts of **Type II**. This family of options involves WPT at microwave frequencies and centralized power management and distribution to the transmitter is centralized (as did **Type I**); however interconnections between sun-pointing and Earth-pointing portions of the platform are provided by reflector systems.

The section that follows describes several **Type II** SPS concepts, including the ISC concept, and the Abacus Reflector SPS concept that were developed during the SERT program. See Table 4-1 for a summary of the characteristics of **Type II** Solar Power Satellites.

Integrated Symmetrical Concentrator SPS

The Integrated Symmetrical Concentrator (ISC) SPS concept is a hybrid concept, highly modular in some regards but including centralized systems for key functions (including power generation and distribution, and thermal management systems). Figure 4-11 presents a conceptual illustration of the ISC SPS concept.

Figure 4-11 Integrated Symmetrical Concentrator GEO SPS Concept



Credit: NASA Artwork, by P. Rawlings / SAIC c. 1998

The ISC closely resembles the Modular Symmetrical Sandwich concept, described as part of the discussion of **Type IV** SPS below. A principal objective in the creation of the ISC concept was to explore an alternative / hybrid SPS system design that might combine the best features of the 1979 Reference System concept and the traditional Sandwich SPS concept, while resolving the significant thermal management challenges of the latter approach. This was accomplished by separating the solar power generation system from the WPT transmitter (as shown in Figure 4-12).

The ISC concept incorporated large, symmetrically placed thin-film concentrator systems to collect sunlight and direct it for conversion via multi-bandgap PV arrays into power. The ISC solar power generation system would have been "body mounted" to the primary transmitter as a strategy to eliminate the critical single/dual point of failure from the "Microwave Classic Update" type concept. (In particular, this eliminated the enormous, high power/high voltage yoke and gimbal system required to connect the PV array and the microwave transmitter in that concept.)

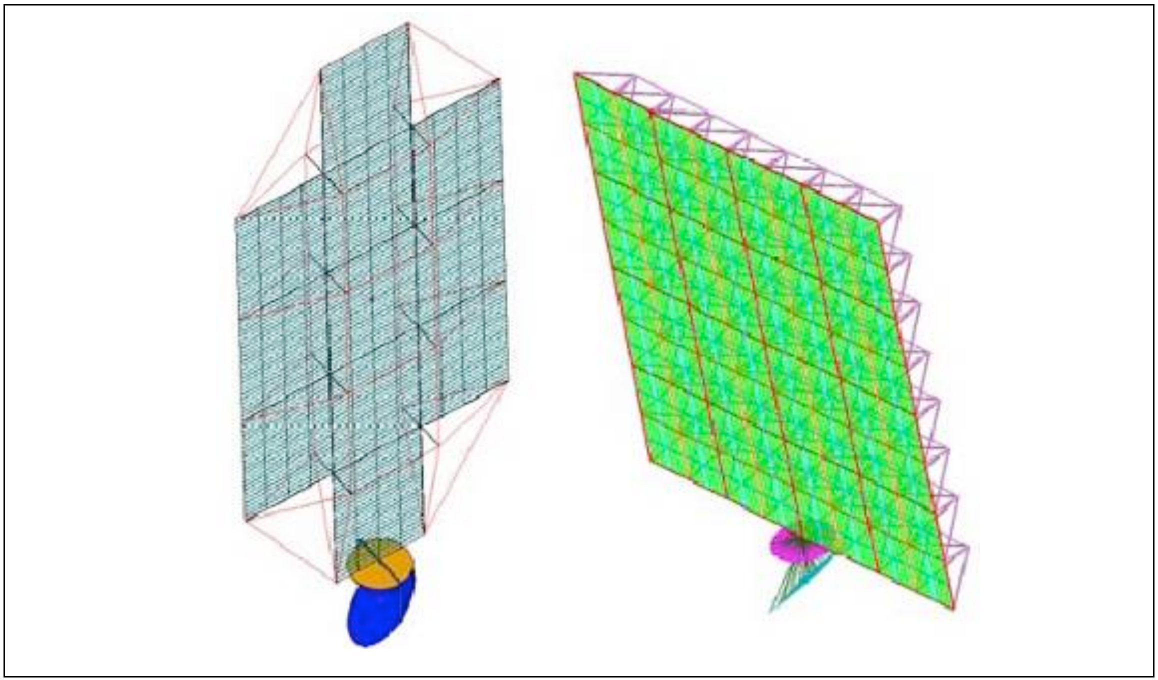
A key advantage of the ISC approach compared to the traditional SPS architecture was the elimination of the very large rotating PMAD system (noted above). A principal disadvantage was that the concept still entailed important, power scale specific system elements (e.g., PMAD) that in turn required several generations of distinct systems development projects – each of which were estimated to require 3-6 years to complete. This idea of planning for multiple generations of systems development at increasing power levels (e.g., 100 kW, followed by 1 MW, followed by 100 MW, etc.) represented a key underpinning of the SSP technology roadmaps presented in 2000 to a committee of the U.S. National Research Council (NRC) for review.[8]

Abacus Reflector SPS

The Abacus Reflector SPS concept also attempts to solve some of the **Type I** SPS's issues via a different sort of reflector; it utilizes a solar array and transmitter that track the sun, and the transmitted microwave beam is redirected by a rotating reflector to bend the beam and send it toward Earth and terrestrial receivers. Thus, the rotation mechanism is placed after the major subsystems that collect the solar energy and generate the microwave power beam. This avoids the technical challenges associated with high voltages passing through large slip rings. See Figure 4-12 below.

The Abacus Reflector SPS concept still involved several highly challenging technologies. First, the reflector below the WPT transmitter must be both rigid and almost perfectly flat, and it must be pointed at the target on the receiver on Earth. Second, the solar power array would still be extremely large, requiring very low mass support structures and low mass PMAD systems. (Recall that for **Type I** systems, this implies the need for very high voltages or for superconducting power management, or both.) Finally, although selected elements (e.g., individual PV arrays) are highly modular in this concept, the system concept still involves several large, integrated systems – likely involving higher costs and significant up-front in-space infrastructure developments.

Figure 4-12 Abacus Reflector Microwave SPS



Credit: NASA Artwork (c.1999)

As a variation on the baseline Abacus Reflector, note that is not essential that the microwave mirror (the reflector at the base) be attached physically to the solar array and microwave transmitter; instead, this system could be free flying in the vicinity of the remainder of the overall architecture. However, in this case, considerable propulsion capability will be needed to maintain the two sections of the overall system in close proximity to one another. (The same is true for the ISC, by the way. The thin-film mirrors might be free flying near the remainder of the platform; however, there is still the problem of how to maintain proximity).

Assessment of Type II Concepts

Type II SPS concepts solve one major design issue of the **Type I** approach: they eliminate the need for transferring large amounts of electricity across a rotating ring connector. As with the case of the **Type I** concepts, moreover, there have been great advances in many of the needed component technologies. However, several of the unique technologies needed (e.g., the extremely large mechanical gimbaled system) have not been developed.

An important technical hurdle for all SPS concepts is that of thermal management. For **Type II** systems of the ISC type, this challenge is significant due to the projected high concentration levels of the incoming solar energy on the body-mounted PV arrays. And as with most new SPS concepts developed since the early 1990s, these approaches will require a variety of advances in robotic in-space assembly and construction (ISAAC) technologies; in this case, these systems will most likely need to be dedicated and stand-alone (i.e., the platforms will not be self-assembling, they will need to assembled by supporting systems).

Overall, **Type II** SPS approaches suffer from several important technical and programmatic challenges, including:

1. Low maturity for key technologies;
2. Potentially high weight due to the large high-voltage PMAD power distribution;
3. Projected up-front development costs for selected monolithic portions of the large platform;
4. Thermal management issues for the ISC (due to higher expected concentration ratios); and,
5. Significant technical challenges for the Abacus Reflector SPS concept due to the requirement for a virtually flat RF reflector (at microwave wavelengths).

Type III SPS Concepts

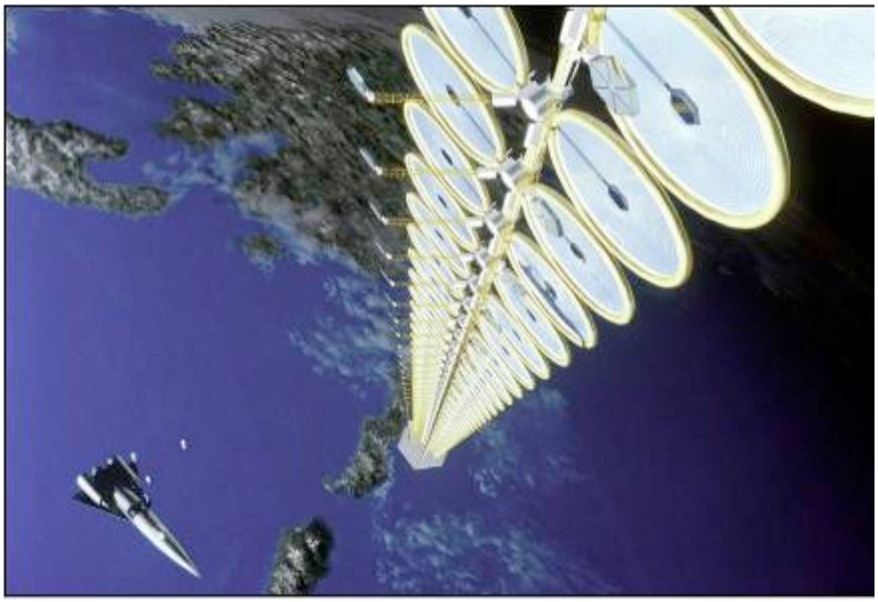
Microwave WPT Systems; Electrical PMAD Interconnects; Modular Architecture; and, Smaller, Locally Gimbaled Systems

The SunTower concept developed during the mid-1990s NASA Fresh Look Study is representative of **Type III** SPS system concepts. This family of options involves WPT at microwave RF frequencies (as did **Type I**); however, interconnections between Sun-pointing and Earth-pointing portions of the platform are provided by reflector systems. Power management at the WPT transmitter is centralized, as were both of the earlier architecture types. See Table 4-1 for a summary of **Type III** SPS characteristics. The discussion that follows sketches the important aspects of the SunTower (and related SailTower) SPS concept.

SunTower SPS

The “SunTower” was one of the most visually interesting and intuitively appealing solar power satellite concepts to emerge from the Fresh Look study in the 1990s. The SunTower SPS can be described as a modular, gravity-gradient stabilized system concept in which power is generated in a series of identical advanced photovoltaic (PV) arrays along a power-transmitting “backbone” which conveys the power generated to a nadir-pointing phased array at the base of the “tower”. Figure 4-13 provides a summary visualization of the SunTower concept.[9]

Figure 4-13 SunTower Modular SPS Concept Based in LEO



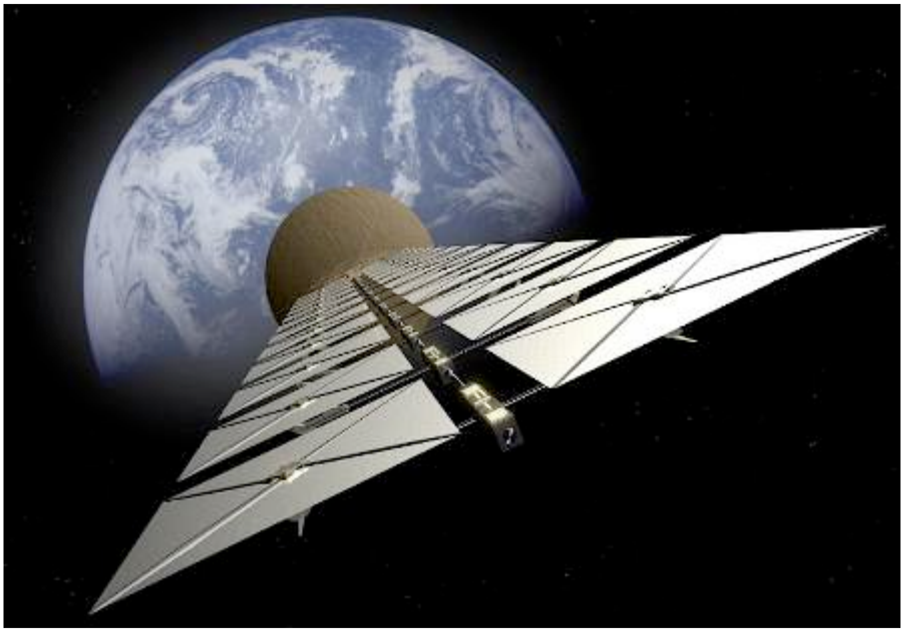
Credit: NASA Artwork, by P. Rawlings / SAIC c. 1996

The SunTower system concept (with some variations) may be deployed into any one of several specific orbits, including: (1) a sunsynchronous (SS) low Earth orbit (LEO), (2) a middle Earth orbit (MEO) with any one of several potential orbital inclinations, and (3) geostationary Earth orbit (GEO). Three cases have been examined to date) with specific orbits. These are: LEO-SS at an altitude of 1,500 km, low MEO at an altitude of 6,000 km and high MEO at an altitude of 12,000 km. For the MEO options in particular, the two sub-cases that have been defined have involved: (a) a constellation of approximately 24 satellites, placed in families of 4 in each of 6 orbital planes, and (b) a constellation of as few as 6 or as many as 30 satellites, evenly-spaced in a common equatorial orbit.

The SunTower SPS concept is a highly-modular, gravity-gradient stabilized platform concept) in which power generation is divided in a large number of identical units for solar power generation, each of which feed power through a central backbone power management and distribution (PMAD) system to an integrated, electrically-steered RF transmitter at the nadir/Earth-pointing end of the platform. Although it could also be located in GEO, the baseline orbit for the SunTower SPS was LEO, as shown in the figure.

A variation on this concept was the later European “SailTower” SPS, which proposed to use thin-film PV arrays in lieu of the concentrator PV assumed for the SunTower baseline. (See Figure 4-14.)

Figure 4-14 European SailTower SPS Concept Based in GEO



Credit: ESA Artwork, provided by L. Summerer

In order to avoid self-shadowing of the SPG elements, the SunTower entailed an extremely long (e.g., tens of kilometers long) backbone. In one case, a large number of comparatively small-scale SunTower SPS would have been placed in a LEO sun-synchronous orbit to provide power during the hours around dawn and dusk at various locations on Earth (complementing ground-based solar power systems). The GEO version of the SunTower inspired the ESA “Sail Tower” SPS concept, in which the individual solar power modules (which were to be concentrator solar power (CSP) modules in the SunTower) were replaced with thin-film PV modules in the Sail Tower case.

Assessment of Type III Concepts

The **Type III** Concepts) like SunTower are technically feasible and demonstrate several potential advantages. For example, the **Type III** Concepts have the advantage that they eliminate the need for an exceptionally large mechanical and power-conveying gimbaled system (which is needed for the 1979 Reference System type SPS). Also, this class of SSP systems is highly modular, permitting a substantial degree of self-assembly. However, they fail to resolve the issue of the large PMAD system – particularly that required for the transfer of power down the backbone of the linear system) and then across the backplane of the microwave transmitter. Also, in the case of a LEO deployment of one of the "Tower" approaches, several of the challenges are mitigated, including the required size of the transmitting aperture for a given size receiver. Unfortunately, **Type III** SPS have several technical and programmatic hurdles to overcome, including:

1. Low maturity for key technologies (including PMAD);
2. Potentially higher weight due to the need to make the "tether backbone" very long to overcome self-shadowing of the solar power arrays around local noon and local midnight in the orbit; and,
3. Projected up-front development costs for selected monolithic portions of the large platform.

Type IV SPS Concepts

Microwave WPT Systems; Reflecting Interconnects; Modular Architecture; and Large, Platform-Level Gimbaled Systems

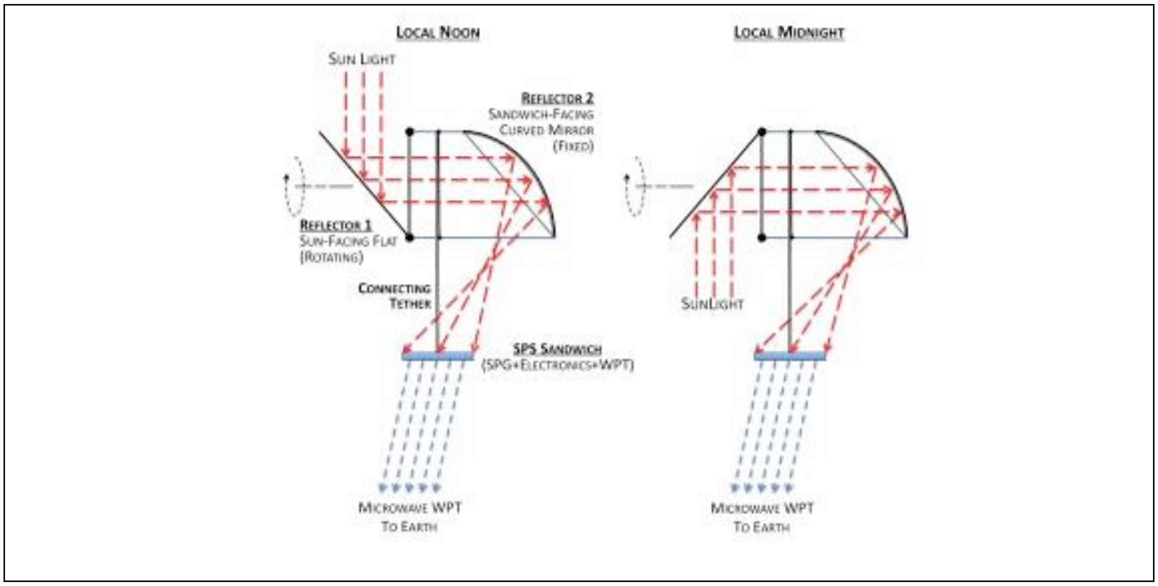
Introduction

A Sandwich SPS approach involving a large, integrated reflector epitomizes the **Type IV** SPS architecture. Although a magnetron RF amplifier might be used, most contemporary **Type IV** concepts almost exclusively involve solid-state power amplifiers rather than electron tubes (either large, such as Klystrons, or small, such as magnetrons). There are two basic approaches: the traditional Sandwich SPS, and alternative reflector configuration.

Traditional Sandwich SPS

The Traditional Sandwich SPS concept that characterizes **Type IV** is one that has been under study by Prof. Nobuyuki Kaya of Kobe University for over twenty years. A simple diagram of one version of this concept is illustrated in Figure 4-15.

Figure 4-15 Traditional Microwave Sandwich SPS



Credit: Artemis Innovation Management Solutions LLC (2013)

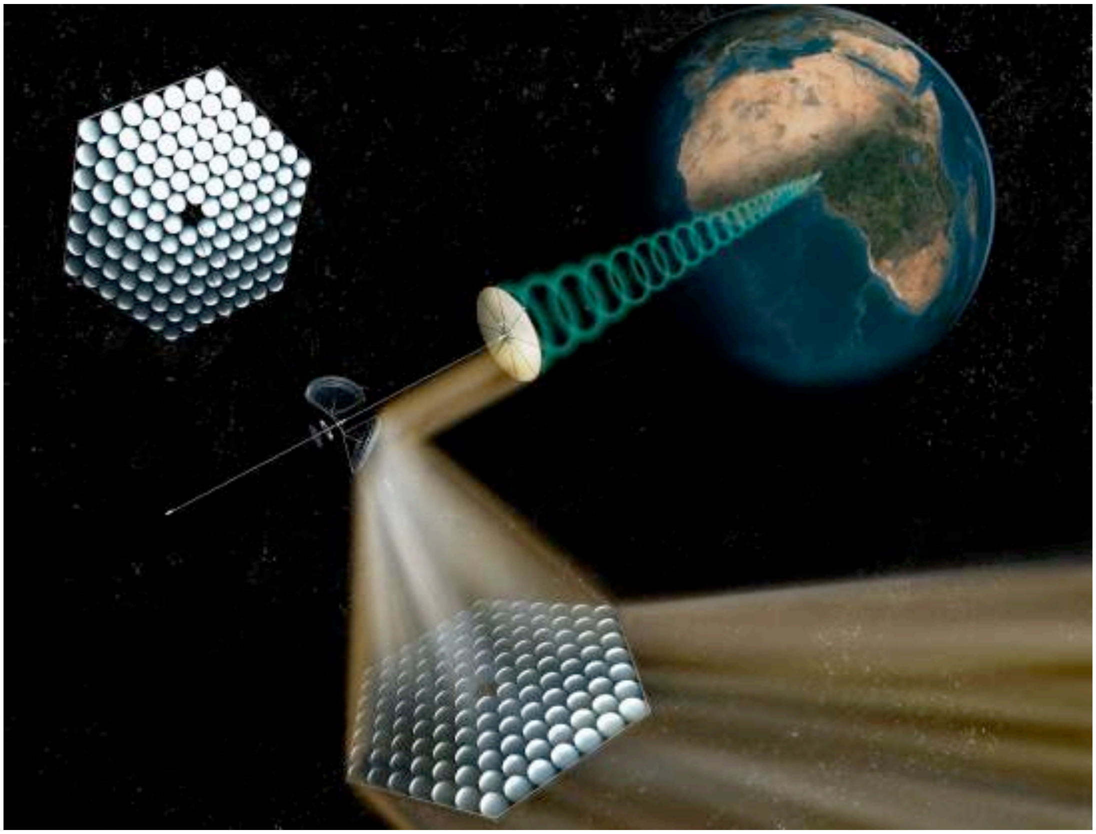
It comprises three major elements: (1) an Earth-pointing sandwich array comprising a great many individual panel segments (involving solar power generation and supporting electronics and wireless power transmission in a single panel); (2) a large, curved, concentrating mirror system; and (3) a large flat mirror that continuously points toward the sun. In these systems, the “sandwich panels” are envisioned as fully integrated systems in which structure, solar power generation, and wireless power transmission functions are combined, along with interfaces that connect one panel to its neighbors.

Modular Symmetrical Sandwich

The **Type IV** Modular Symmetrical Sandwich Type SPS (like the **Type II**) lends itself to modular, robotically assembled platform concepts and a significantly reduced requirement for an *a priori* in-space infrastructure for ISAAC. Figure 4-16 presents an illustration of this concept; the heritage to the ISC concept is clear.

Whereas the traditional Sandwich SPS redirects and then concentrates the incoming sunlight (so that both reflectors are large), the Modular Symmetrical Concentrator concentrates and redirects at the first reflector (so that the secondary reflectors are much smaller). The nature of the concept implies that technology maturation and demonstration will be relatively straightforward within individual modular elements – primarily of the main SPG/PMAD/WPT structure lending themselves to affordable R&D efforts.

Figure 4-16 Modular Symmetrical Sandwich SPS



Credit: SpaceWorks Enterprises, Inc. (2010)

An important disadvantage of the Sandwich SPS concept is the requirement that a novel solution must be found for the transmitter/PV module Thermal Management System (TMS). Failing to find a TMS solution, an architecture level solution might involve limiting the peak power transmitted per square meter on the array, thus requiring either a departure from a 10-to-1 taper Gaussian distribution across the transmitter or a drastic reduction in the total power transmitted.

The capability of the electrically beam steered sandwich RF transmitter could enable new types of markets and the potential to serve multiple markets simultaneously (or nearly so). If the power from a single SPS were shared among multiple receivers, then a larger aperture transmitter (and proportionately smaller receivers) could become viable without exceeding RF energy intensity guidelines at any single receiver site.

Assessment of Type IV Concepts

The **Type IV** SPS concepts (along with **Type V**, described in the following section) were judged in the recently completed IAA assessment of SSP as preferred over either of the two traditional SPS (labeled **Type I** here). Probably the greatest shortcoming of the **Type IV** SPS concepts derives from their reliance on extremely large integrated reflectors (albeit perhaps with numerous small sub-reflectors). This implies construction issues, higher system costs; and significant operational risks due to the existence of single points of failure. Although not required to carry voltages – a great improvement over various earlier SPS architectures –**Type IV** SPS rotary joints are still vulnerable to micrometeorite damage or simple mechanical failure. Because they are essential to system operations, a failure of any kind could stop power delivery until repairs can be completed.

Type V SPS Concepts

Microwave WPT Systems; Reflectors as Interconnects; Hyper-Modular Architecture; Power Management; and Small, Local-Level Gimbaled Systems

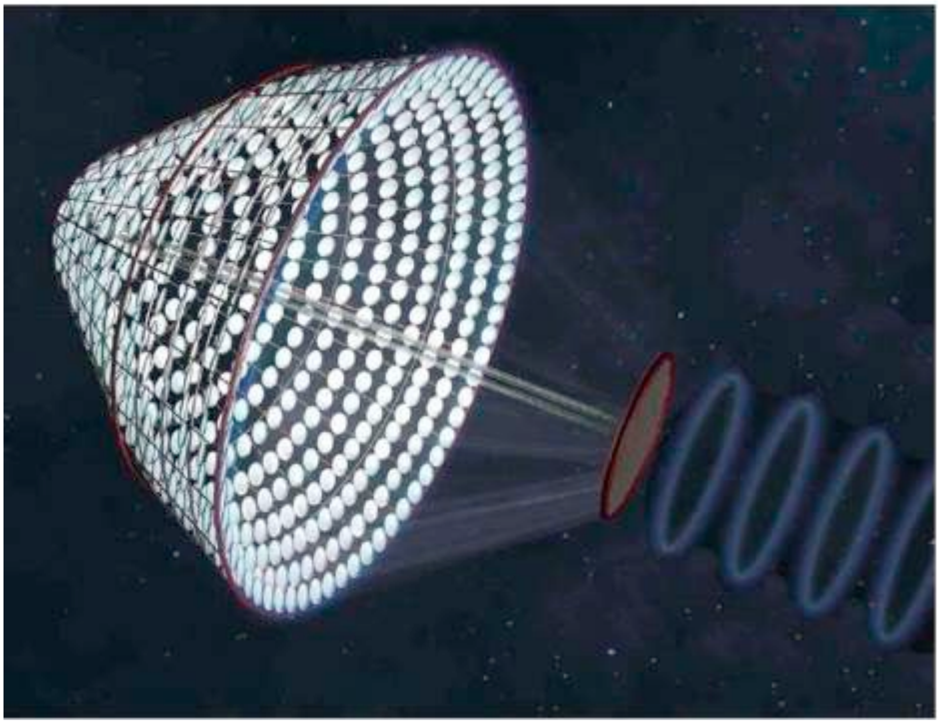
Introduction

The **Type V** SPS concepts are new in the literature of SPS; they emerged with a proposal in Spring 2011 to the NASA Innovative Advanced Concepts (NIAC) Program, and are epitomized by the SPS-ALPHA (Solar Power Satellite by means of Arbitrarily Large Phased Array) concept.

SPS-ALPHA

The **Type V** integrated modular Sandwich Type SPS (like the **Type IV**) lends itself to modular, self-assembling platform concepts and a significantly reduced requirement for *a priori* for in-space infrastructure for ISAAC. The nature of the concept implies that technology maturation and demonstration will be relatively straightforward within individual modular elements – primarily of the main SPG/PMAD/WPT structure lending themselves to affordable R&D efforts. Figure 4-17 presents an early illustration of the SPS-ALPHA concept.

Figure 4-17 The SPS-ALPHA Concept as Proposed in 2011



Credit: J. Mankins Concept / Art by SpaceWorks Enterprises, Inc. (2011)

As was the case with the Sandwich SPS concept, a disadvantage of SPS-ALPHA and related variations is the requirement for a novel solution for the solar power generation and transmitter modules in the primary array at the base of the platform. Failing to find a workable TMS for high concentration, an architecture level solution might involve limiting the peak power transmitted per square meter on the array, thus requiring either a departure from a 10-to-1 taper Gaussian distribution across the transmitter or a drastic reduction in the total power transmitted.

Also, just as in the Sandwich SPS case, the electronically steered microwave WPT transmitter could enable new types of markets and the potential to serve multiple markets simultaneously (or nearly so). If the power from a single SPS could be shared among multiple receivers, then a larger aperture transmitter (and proportionately smaller receivers) might become viable without exceeding RF energy intensity guidelines at any single receiver site.

Assessment of Type V Concepts

At present, there is only a single SPS architecture in this class: SPS-ALPHA. As we will see later, however, there are a great many alternative topologies within this basic approach. SPS-ALPHA eliminates the major weakness of **Type IV** SPS Concepts: the single point of failure represented by the larger reflector design involved. It also greatly enhances the potential to employ gravity-gradient stabilization.

Type VI SPS Concepts

High-Frequency WPT Systems: Typically Electrical, but Varying as Interconnects; Typically Modular, but sometimes Monolithic Architecture; and Typically Platform-Level, but sometimes Local Gimbaled Systems

Introduction

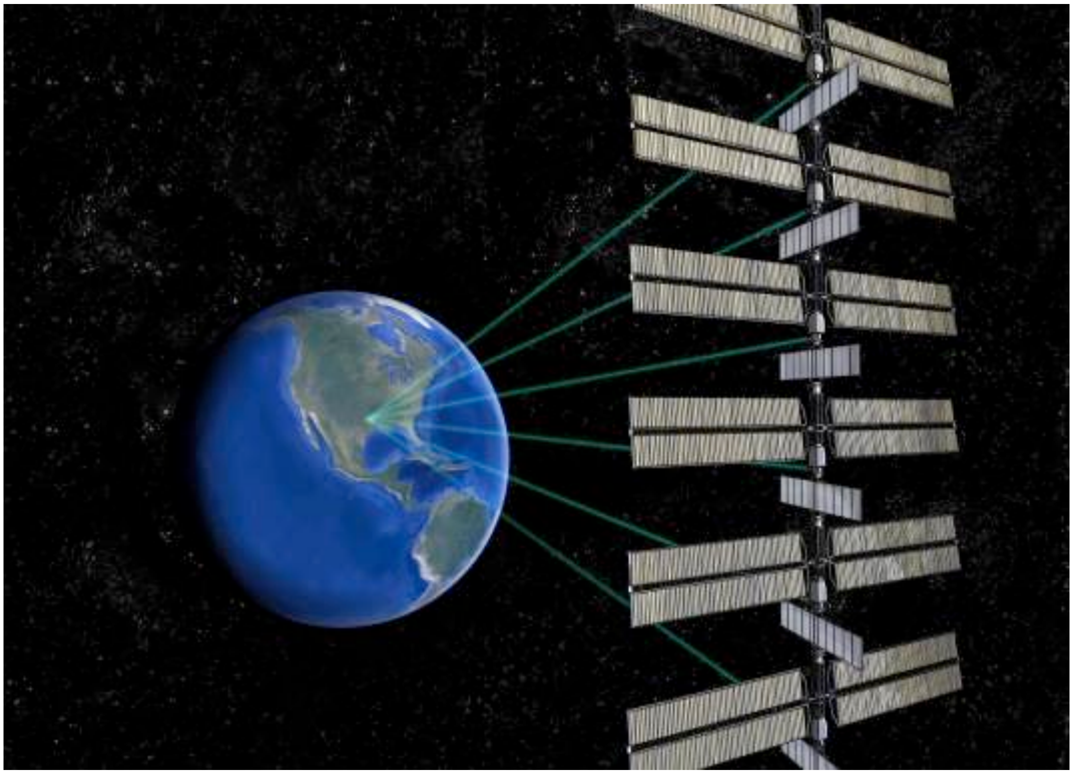
A fundamentally different path for solar power satellites is to choose to employ high-frequency wireless power transmissions systems; these systems involve either near visible or visible laser wavelength, or what are known as "millimeter-wave" (mm-wave) RF emissions (about 1/100th the wavelength of microwaves).

GEO-Based Modular Electric Laser SPS

In this case, an SPS using laser power transmission would be assembled from a number of discrete, but fairly large individual modules; for example if a given module delivered some 10 MW of laser power to a ground receiver, the 100 such modules would be needed to deliver a total of 1 GW. Figure 4-18 presents an illustration of this approach to space solar power, oriented in that image as a 3-axis stabilized platform that is perpendicular to the plane of the platform's orbit. Typically, this type of SPS would use an electric laser technology approach (e.g., an array of diode lasers), and would transmit at or near the visible portion of the spectrum to take advantage of the "window" in Earth's atmosphere at those wavelengths. (We discussed this at the beginning of this Chapter.)

The ground segment for this SPS concept would be quite different from those of other microwave WPT platforms: the receiver would be a PV array, using PV cells fabricated from doped semiconductors that are "tuned" to efficiently convert the specific wavelength of the laser. It this way, end-to-end power transmission can be must more efficient than otherwise. Despite this, the power transmission efficiency for laser WPT is projected to be significantly less than that achievable by large-scale microwave power transmission (i.e., no more than 10%-15% for the laser system versus as much as 40%-50% or more for the microwave system).

Figure 4-18 Modular Electric Laser SPS



Credit: SpaceWorks Enterprises 2011

This concept has the advantage that it is not necessary to establish a large coherent aperture across some 100s of meters – as was required for the microwave concepts we discussed above. However, because the number of modules is much fewer (i.e., 100s versus 100s of thousands), the costs for such a platform will inevitably be higher. Moreover, transmission at a near-visible frequency also means that haze or cloudy skies will block the power transmission.

GEO-Based mm-Wave or Laser SPS with Atmospheric Relay

One alternative approach to the near-visible laser SPS concept is to use infrared lasers (IR) that cannot pass through the atmosphere (or similar millimeter-wave high power transmitter with the same characteristic). Of course, if the WPT transmission for the SPS in GEO cannot penetrate the atmosphere, then there is no risk of harm to humans or animals on the surface – however, no power will be delivered! The solution in this concept is to introduce a very high altitude relay station, such as a balloon or airship that would be tethered to a particular spot on

Earth and suspended above the appreciable atmosphere. That platform, which would be perhaps positioned at 200,000 feet, would receive the incoming laser (or high frequency RF) transmission, convert it to electricity and then transmit it on to a receiver on the surface. This second transmission might be done via microwave WPT, or perhaps by using the tether itself as a power transmission line.

GEO-based Solar-Pumped Laser SPS

Yet another SPS concept in this general class uses a solar-pumped laser WPT; this concept would be based on the phenomena of direct stimulation of laser emissions by concentrated sunlight. It has the theoretical advantage of avoiding the efficiency losses that occur at the solar power generation, power management, and wireless power transmission system stages of other SPS concepts. Figure 4-19 provides an illustration of a JAXA concept for a solar-pumped laser type SPS.

Figure 4-19 Solar-Pumped Laser SPS Concept (by JAXA)

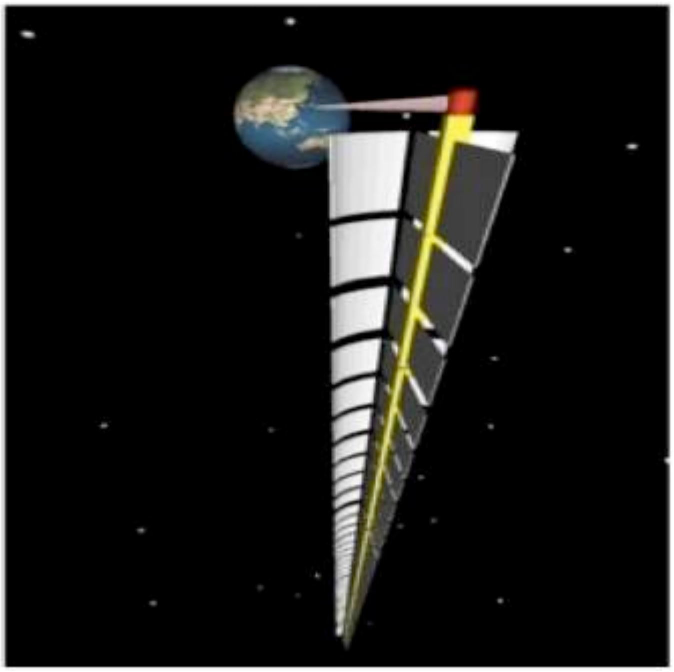


Image Credit: JAXA

This concept was developed several decades ago when the efficiencies that could be achieved by solid state, electrical laser systems were extremely low; the solar pumped laser option offered potentially much higher efficiencies. This system concept requires both optical systems for the collection of incoming sunlight and its precision delivery to the laser, and directional systems to guide the resulting laser light to the desired receiver on Earth.

Several critical technology challenges remain. First, it is unclear how the concept could achieve assured fail-safe operations (without the risk of weaponization). Second, solid state lasers have now achieved good efficiencies, with the promise of much higher performance within the next several decades, however they are projected to always be lower than microwave WPT efficiencies.

Assessment of Type VI Concepts

The most obvious advantage of laser-type SPS concepts is the exceptionally high frequency (short wavelength) of the beam and the correspondingly small transmitter and receiver apertures that are thereby enabled. As a result, the system's "Cost to First Power" for an operational system element is lower for a laser type SPS than for any other case. Also, the laser (or millimeter-wave) SPS lends itself to modular, self-assembling platform concepts and a significantly reduced requirement for an *a priori* in-space infrastructure for ISAAC.

A number of critical technology advances are required to approach economic viability for a **Type II** SPS using laser WPT. These advances also result in a more challenging set of lower TRL technology R&D goals and a less favorable technology readiness and risk assessment that for the **Type III** SPS.

From the standpoint of the receiver and transmitter optics, the economically optimum design option for near-visible laser WPT SPS involves a small diameter receiver with multiple-sun energy densities per square meter and a relatively large telescope aperture for the beam expander on the platform. However, this approach is not the best for a number of other design considerations. For example, thermal considerations drive platform designs toward smaller, individual, laser diode arrays. Also, safety and policy considerations related to potential weaponization of the SPS system, much smaller on-orbit apertures militate in favor of smaller apertures. These factors, coupled with others, resulted in the decision to baseline much lower beam energy densities than were in this IAA study.

Assessment of Type VI Concepts

The greatest – perhaps the only – advantage of **Type VI** concepts is the potential to dramatically reduce the diameter of the WPT transmitter on the SPS due to the extremely short wavelengths involved; however, these concepts bring with them a number of flaws. These include:

(1) Poor end-to-end WPT efficiency;
(2) Poor and variable transmission through the atmosphere;
(3) Hazards to humans and animals (retinas, etc.);
(4) Increased high development costs; and,
(5) Risk of weaponization (vis-à-vis targets on Earth and in space).

Other Types of SPS Concepts…

Introduction

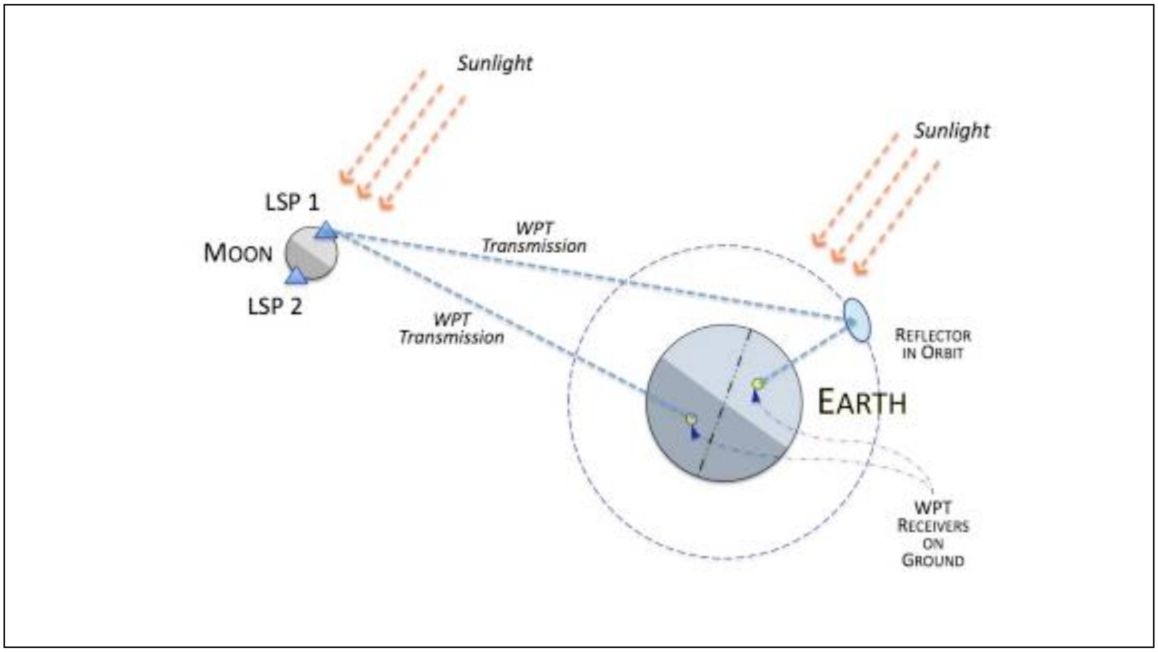
As we discussed earlier, there are a variety of additional SSP concepts that don't fall neatly into one of the six categories described previously. Each of these approaches attempts to resolve one or more of the issues found in the 1979 SPS Reference System. For all of these, however, significant new issues emerge as a result of the design options chosen to resolve earlier issues.[10] The options summarized in the paragraphs that follow include:

Lunar-based Solar Power (LSP);
Libration Point SPS;
Space-Based Mirrors;
Microwave Swarms; and,
SPS Demonstrations Concepts.

Lunar Solar Power

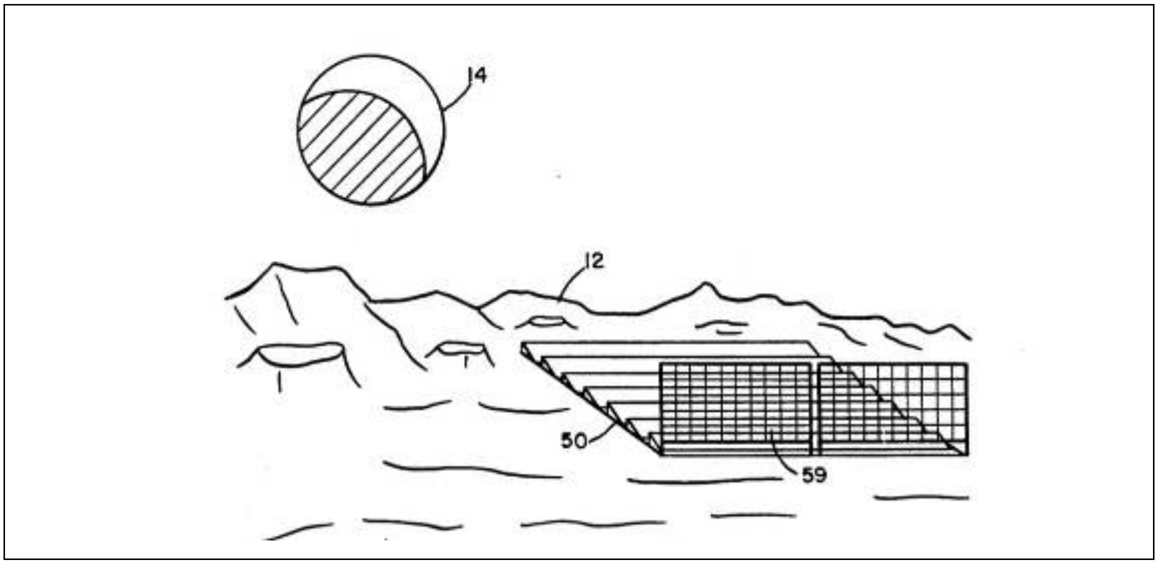
Lunar Solar Power (LSP) is the concept of locally manufacturing, deploying, and delivering power from space solar power systems on the lunar surface. Dr. David Criswell of the University of Houston invented the LSP concept during the 1980s.[11] Figure 4-20 provides a high-level conceptual illustration of the overall architectural concept showing the transmission from the Moon to Earth; Figure 4-22 presents a figure from Dr. Criswell's LSP patent showing one potential implementation of the system on the surface. As illustrated, the concept would involve multiple distinct power stations on the surface. Two examples, labeled as “LSP 1” and “LSP 2,” are shown in the figure. These might be positions on opposite edges of the Moon’s disc as seen from Earth so that at least one of them would be constantly illuminated by the Sun. In addition, because the Moon can only be observed from one side of Earth at any given time, the figure illustrates the additional requirement for large reflectors in Earth orbit that would redirect the WPT transmission toward the side facing away from the Moon.

Figure 4-20 Lunar surface-based Solar Power Concept Overview



Credit: Artemis Innovation Management Solutions LLC (2013)

Figure 4-21 Lunar Solar Power Concept as it Might Appear on the Moon



Credit: US Patent and Trademark Office; Patent No. 5019768

The principal advantage of the LSP concept is that it minimizes the operational mass launched from Earth per kW-hour delivered to terrestrial energy markets. LSP dispenses with the need for exceptionally low cost ETO transport or large scale ISAAC platforms in LEO or GEO. However, LSP faces several tough technological hurdles and entails the greatest amount of upfront infrastructure investment of any SPS concept in that it requires initial installation of large-scale infrastructure on the Moon prior to the beginning of power system construction.

At the architecture level, a key issue for LSP is the increase in the distance over which WPT must occur: 384,000 km for the Moon, versus approximately 36,000 km for GEO. Because of this increase in distance, the diameter of an RF transmitter must also increase by a factor of 10 – resulting in an increase of approximately 100-fold in the area in order to maintain the size of the receiver on Earth at about the same diameter (some 10 km) as the GEO case. However, the number of active transmitters (think of it as millions of cell phones all sending together) varies with the square of the diameter. So, if the transmitter on the Moon is 10 times greater in diameter, it is 100 times greater in area with 100 times more transmitting elements. For an active beam-steering transmitter, this means an increase of 100-times in the number of phase shifters and active electrical sub-elements – and 100 times more cost.

And, of course, the Moon is only in the sky over a particular location on the Earth for a few hours during each day. In order for a large—perhaps as many 100s of gigawatts—LSP system to deliver energy to markets around the Earth, some system of large reflectors in Earth orbit will likely be needed. These reflectors would more than likely be placed in GEO, and they would redirect the energy from the Moon down to a receiving site on the Earth. If the LSP concept is to be viable, then these reflectors will need to satisfy three requirements. First, they must be capable of continuously redirecting the incoming power beam from the Moon to one or more desired targets on the Earth. Second, they must be 'flat' physically or electronically (e.g., they must be like the flat mirror used in the hallway or the powder room, instead of a curved mirror like those found in carnival fun houses).

Finally, if they are to provide continuous power to a given location on Earth (a principal advantage of SPS), WPT transmissions would require the positioning of huge relay satellites in high Earth orbit, all of which would require physical pointing or large numbers of phase-shifting sub-elements – adding another layer of complexity to the concept. The Moon doesn't actually have a "dark side," although there is a "back side" that always faces away from Earth as the Moon rotates once every 28 days, the same time it takes to orbit around the Earth. (This "back side" was unseen until a robotic spacecraft from the USSR first orbited the Moon in the early 1960s.) As a result, the Moon constantly keeps the same face toward the Earth. This results in lunar daylight 14 days in duration and a lunar night of identical length for most of the lunar surface.

If microwave WPT is used, the size of the LPS reflectors (or relay satellites) will be enormous. This is a result of the physics of power beaming (discussed above). Just as the size of a WPT receiver on the ground would be large for an SPS in GEO, the size of a WPT reflector in GEO for Moon-to-Earth WPT must be large. Recall that for a transmitter with a diameter of 1 to 2 kilometers (about 6-12 football fields) in GEO, the receiver on the Earth must have a diameter of 5 to 10 kilometers (about 30-60 football fields). If LSP is to compete with other SSP options, all of these systems must cost less than full scale SPS in GEO would cost.

Libration Point SPS

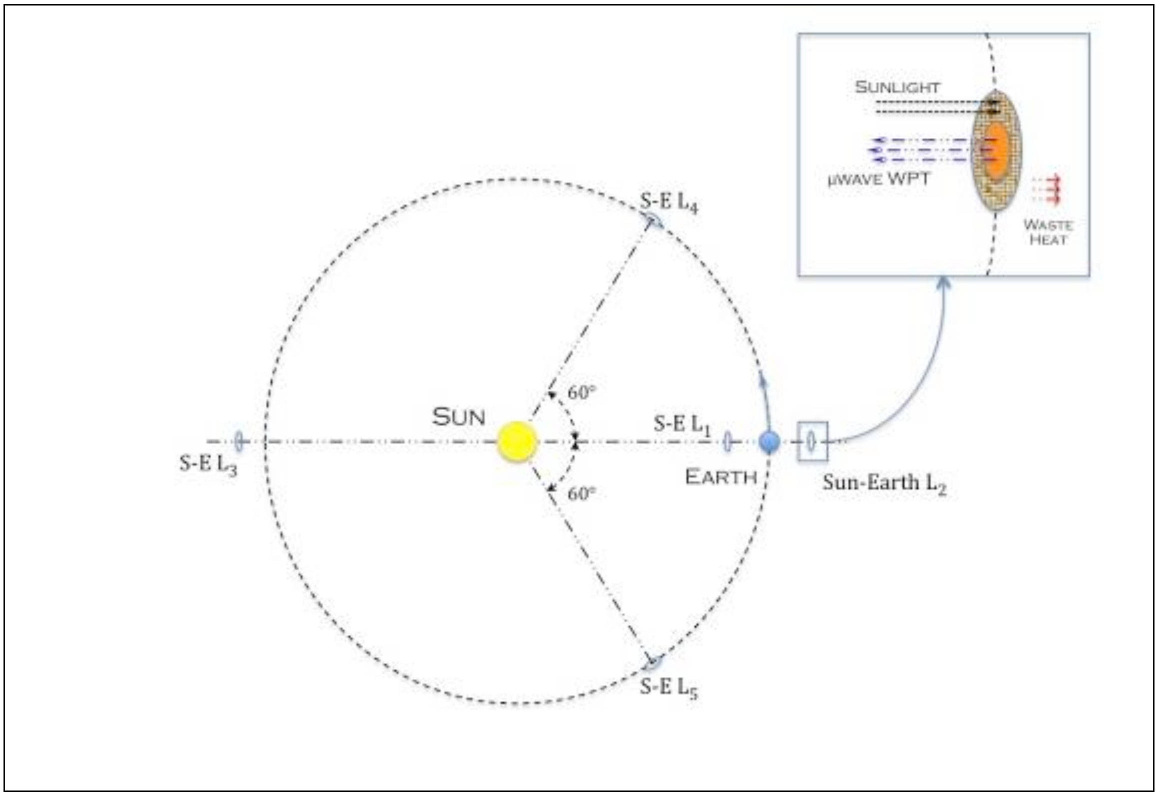
From the Sun-Earth L-2 Libration point, an SPS can be continuously illuminated from the same side of the spacecraft that transmits power to Earth. This allows the back side of the satellite – facing cold space – to be used as a more efficient radiator of waste heat into space. Figure 4-22 provides a high-level illustration of the Sun-Earth L2 Lagrange Point SPS concept. (Dr. Geoffrey Landis of NASA Glenn Research Center (GRC) originally conceived of this approach.)

The principal difficulty with the Libration Point SPS concept is that the distance from Earth to the Sun-Earth Lagrange Point L2 is approximately 1.5 million kilometers – about 40 times more distant than GEO. As a result, for a given frequency, the same receiver size on Earth would require a transmitter with a diameter 40-times greater than an SPS in GEO (or, approximately 1,600-times greater in area, mass and cost). In addition, continuous delivery of power to terrestrial markets would require Earth-orbiting rigid RF reflectors as is the case for the LSP option.

Space-Based Mirrors (Sunlight Reflected to Earth)

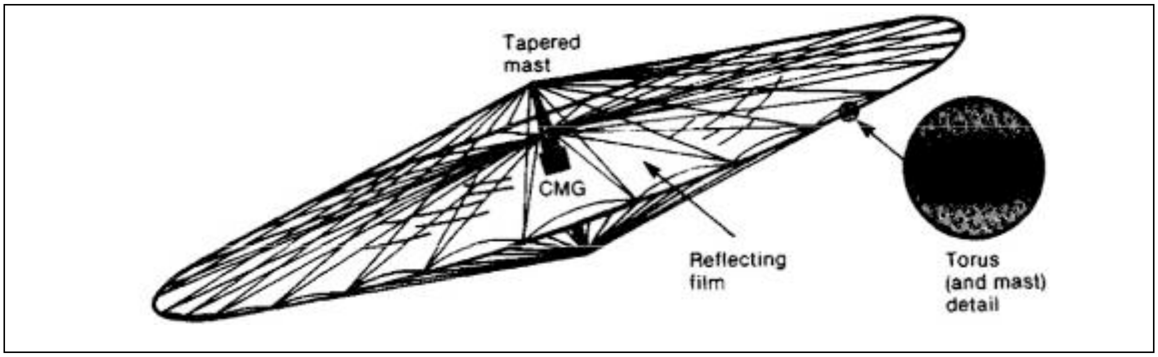
This option is not, properly speaking, a solar power satellite of same type as that invented by Dr. Peter Glaser in the 1960s. Rather, this is the idea of placing large, lightweight mirrors in Earth orbit that would directly reflect sunlight down to solar arrays positioned on Earth. This idea has an inherent appeal: what could be simpler than simply using a mirror to send power down from space? Figure 4-23 presents an illustration of this concept. (This concept, known as "Solares," was discussed as an option during the late 1970s, and from time to time since then.)

Figure 4-22 Sun-Earth L2 Lagrange Point SPS Concept



Credit: Artemis Innovation Management Solutions LLC

Figure 4-23 Solar Reflector in Earth Orbit Concept



Credit: US Congressional Office of Technology Assessment (c. 1980)

The concept of the Earth orbiting reflector has the following advantages: (1) no requirement for energy conversion systems on the spacecraft (i.e., no PV arrays); (2) no need for electronic wireless power transmission systems (i.e., no microwave phased array or laser systems); and (3) no requirement for either power management and distribution or thermal management systems on the spacecraft. However, there are a number of significant technical challenges that make this concept far less promising than it might otherwise appear.

Firstly, reflected sunlight is entirely subject to the effects of weather; overcast, haze, and atmospheric refraction will all affect the reflected light. Although the sunlight may be delivered continuously from a mirror in space, that light will only reach a receiver on the surface during a fraction of that time; only a portion of the initial energy will arrive. (Recall that sunlight in space at Earth has an energy density of roughly 1,350 W/m^2, whereas sunlight at midday near the equator on Earth has an energy density of roughly 1,000 W/m^2.)

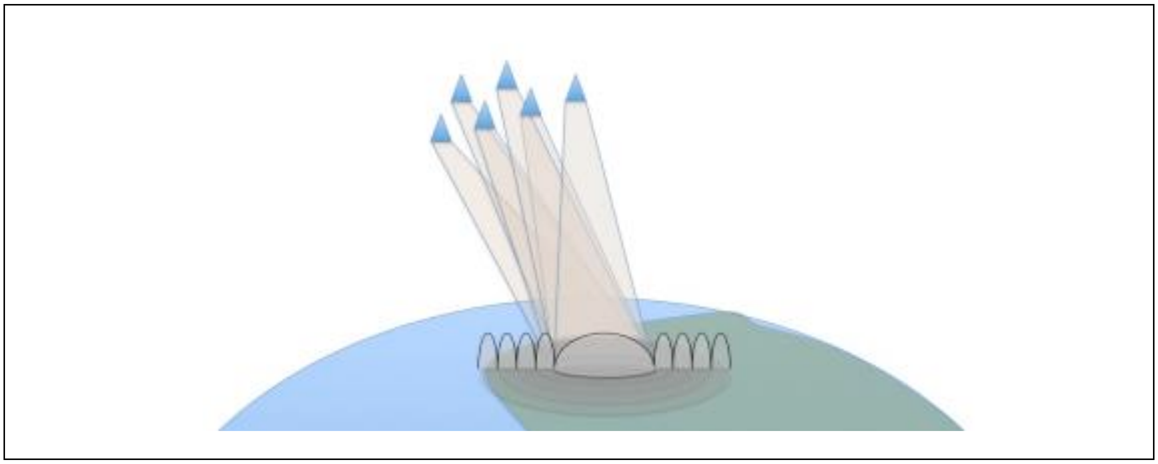
Moreover, even though it is roughly 150,000,000 kilometers distant, the sun is a finite object in the sky and the rays of sunlight coming from it are not parallel. As a result, the light that makes up the image of the sun reflected from a mirror spreads out with distance from the mirror. In the case of a 1 meter diameter mirror positioned in geostationary Earth orbit (an altitude of roughly 35,800 km), the size of the reflected spot of light at a location on Earth would be several hundred kilometers in diameter. In order to deliver solar energy at an intensity of roughly “1 sun” (i.e., 1,000 W/m^2) at Earth, a mirror in GEO orbit would also need to be several hundred kilometers across.

Finally, because of the scale of the mirror required, the technology challenge involved in its construction would be immense. The solar reflecting mirror in orbit must be optically flat (to a fraction of a wavelength of light), over an area 100s of kilometers in diameter and 10s of thousands of square kilometers in area. For comparison, the mirror surface of the James Webb Space Telescope (JWST) now in development is only 6.5 meters in diameter. In addition, the size of the ground receiver would be on the order of 100 km in diameter or more and would require dedicated utilization by conventional solar arrays across this area. Fundamentally new approaches to large space reflector systems will be required (i.e., the current technology readiness level for this concept is TRL 2 or less).

Microwave Swarms

Another idea that is occasionally discussed is that of a hyper-modular extremely large constellation of small SPS platforms – a swarm of satellites. Each of these satellites would be about the size of a large current technology GEO commsat and capable of being launched intact on a single launch vehicle. Two different version of the swarm approach to SSP are discussed. The first is a swarm of spacecraft that employ ultra-high frequency EM waves (i.e., lasers in the near-visible, or high frequency RF, known as "millimeter-wave") for individual power transmission to receivers on Earth or in space. The idea of a laser or millimeter-wave WPT swarm is described previously in the discussion of modular laser WPT options. The other idea proposes to use microwave WPT, but with the various separated emitters "phased" correctly to produce coherent EM waves. Figure 4-24 illustrates this approach.

Figure 4-24 Microwave WPT SPS Swarm



Credit: Artemis Innovation Management Solutions LLC (2013)

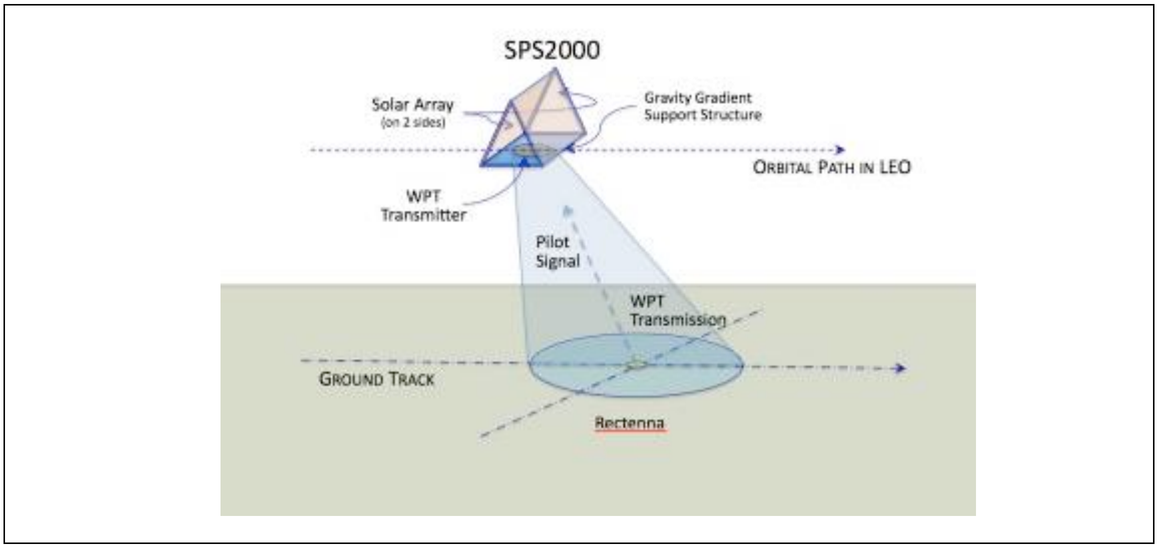
The microwave WPT swarm concept has a number of promising features – which is why it keeps reemerging. For example, it requires no large-scale structural system to hold the parts in place. Also, it is very "hyper-modular," with every piece a standalone spacecraft. Unfortunately, the RF swarm SPS concept is fatally flawed. First, two or more unconnected objects in orbit around the Earth cannot stay near one another without using propulsion (or some other force); each must move in its own individual orbit, and over time any cluster of objects will diverge. (This tendency to disperse gets worse the larger the number of elements – and the greater the separation from edge to edge – in the swarm.) Second, and much more damaging to the concept as we discussed at the beginning of the Chapter, disconnected RF transmitters – even if they are in phase with one another – will be in what is called a "sparse array." As a result, they will "spill" increasing amounts of RF energy into "grating lobes" away from the intended target, the greater the separation between the elements.

Demonstration Concepts

SPS2000. The SPS2000 concept was actually targeted on demonstrating the concept of Space Solar Power from LEO. Figure 4-25 provides an illustration of the SPS2000 SPS concept. It was fully passive, with a "tent-shaped" structure and solar array over the top of an Earth-pointing phased array microwave transmitter. In one conception, the SPS2000 would transmit about 10

MW from the WPT system and, because of the non-pointing character of the structural system, would generate anywhere from no power to roughly 60-70 MW of power on board the platform.

Figure 4-25 SPS2000 Microwave WPT SPS



Credit: Artemis Innovation Management Solutions LLC (2013).

Flat-Plate Sandwich Demonstration SPS. During recent years, JAXA ISAS SSP project team has been looking at a potential demonstration configuration for the Sandwich SPS that would involve a gravity-gradient, stabilized, flat-plate space platform that would only generate and transmit power when the platform (which would always point at Earth) had the sun overhead. Figure 4-26 provides an illustration of the gravity-gradient stabilized flat-plate sandwich SPS demonstration concept.

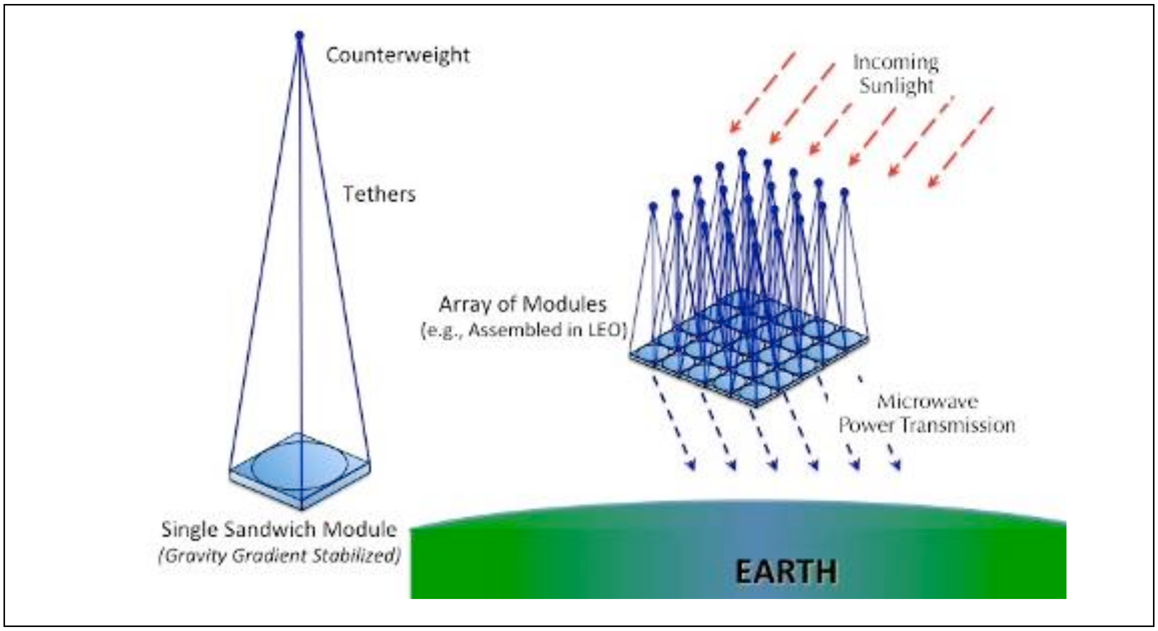
As illustrated, the Flat Plate concept would be a gravity-gradient stabilized array of microwave sandwich panels (with PV cells on the side facing away from Earth and microwave antennas on the side facing Earth). It would not use any optical systems to redirect sunlight to fall on the PV cell size continuously; as a result the power would vary greatly during the course of each orbit.

It is also possible that this SPS architecture could be considered for an operational system. In this case, to increase power output, PV cells might be placed on both sides of the sandwich modules (facing toward Earth and facing away from Earth). This change would improve the total energy output (which would still be far less than **Type IV** or **Type V** SPS concepts with reflectors). However, placing PV cells on both sides would pose significant design issues (i.e., integration of the PV array with the RF transmitter) and major thermal management issues.

Assessment of Type VI Concepts

As promised, the SPS concepts grouped under the category "**Type VI**" represent a wide variety of different ideas that have relatively little in common. As a result, a systematic assessment is rather difficult; nevertheless, I would like to offer some general observations on this group. It is important to note that all of these options except the last attempt to solve some important technical hurdle associated with the 1970 SPS Reference concept.

Figure 4-26 Flat Plate Microwave WPT Sandwich SPS (Demo)



Credit: Artemis Innovation Management Solutions LLC (2013)

A couple of the concepts look at changing the location of a prospective SPS to gain a particular architecture-level advantage. LSP (Lunar Solar Power) proposes to place the SPS systems on the Moon in order to gain the maximum advantage from the use of lunar resources in their construction. Similarly, the Sun-Earth Libration Point SPS concept proposes to relocate the platform from GEO to a point in space where the large, high-voltage rotating couplings used in conventional SPS architecture would no longer be necessary because the relative positions of Earth and the Sun don't change.

The "Solaris" approach (using a large in-space mirror) attempts to completely eliminate the need for solar power generation and wireless power transmission by simply reflecting sunlight down to photovoltaic arrays on Earth. This could be done with good efficiency, of course – at least when there is no intervening haze or weather. As discussed previously, there are significant problems with this concept.

And, of course, the final entry in this category is not actually a Solar Power Satellite at all, but is instead the general notion of SPS demonstration platforms.

Evaluation of Selected Types of SPS

There are clear distinctions that can be drawn among the principal candidate SPS system concepts and related supporting systems. The following is an "apples-to-apples" evaluation of the several approaches in terms of common criteria within the context of the projected market for SPS-delivered energy.[12]

Triage on Some Interesting Ideas that Won't Work

Before turning our attention to the evaluation of the various types of SPS described above, it makes sense to do a quick *triage* on a few ideas that are attractive, but for one reason or another won't work. From time to time, people have proposed approaches to SPS that just don't work, either for reasons of physics or of practicality, or a combination of the two. There are some fundamental considerations, based in large measure on the physics-based constraints discussed at the beginning of the chapter that may be used for this initial step. These include the following factors:

> SSP system and WPT transmitter Size;
>
> SSP system placement / location, which affects receiver size and number of receivers required;
>
> End-to-end energy conversion and wireless power transmission efficiency; and
>
> The cost of space-based systems versus terrestrial systems.

With just these factors, several concepts may be immediately dropped from further consideration. The concepts described above include a few that come close to falling into this category, but not quite. The ideas below are far from technically feasible, and so I mention them here for the sake of completeness. Please don't infer that I think they should be considered seriously.

Interplanetary Power. In his 1953 novel "Caves of Steel," Isaac Asimov first suggested the concept of transmitting power over interplanetary distances. In a conversation between the protagonist in the story and another character, the idea is suggested of deploying energy harvesting stations inside the orbit of the planet Mercury, which would then "transmit energy to Earth by direct beam." This idea is raised from time to time. Unfortunately, it will not work – due to the issue of diffraction-limited optics that we discussed at the beginning of this chapter.

As Asimov had his protagonist point out in the story, it was impossible to transmit energy over fifty million miles "without dispersal to uselessness."[13]

Space-based Power Grid. During the Fresh Look Study, we looked at the idea of using space-based platforms and wireless power transmission to transport power from locations on Earth where it was available to markets where it could be sold. This concept of a Space-based Power Grid is very appealing. After all, why not generate solar power in the desert and beam it via space platform to markets in northern Canada, or Siberia, or…? (Buckminster Fuller once proposed a global scale, ground-based power grid to solve this same problem.) Unfortunately, the Space Power Grid – although very interesting and appealing –wouldn't work economically. There are several reasons. First, transmitting the power from a point on Earth requires the maximum energy intensity to be near living things and sent through the atmosphere – a potentially hazardous operation, and one that would not be performed continuously.

Second, the transmission will spread out as it leaves Earth; the converted and retransmitted energy in space (which might be reflected) would spread still further in returning to Earth – resulting in a receiver diameter much larger the size of the corresponding space-to-ground power system. Also, and more importantly, the additional interconnecting WPT links in the chain from generator to customer severely degrade any potential economic opportunity. (For example, with a microwave WPT system, at best one *might* achieve: uplink at 70%, transmission through the atmosphere and reception at 92-94%, conversion in space at 85%, retransmission at 70%, transmission and reception at 92-94%, and finally reconversion at the market receiver at 85% – resulting in an end-to-end efficiency of less than 30%, far too low, at a cost far too great to ever compete with conventional power lines.) And finally, if part of the business model is to contribute to addressing greenhouse gas emissions, then most terrestrial energy sources (i.e., those involving fossil fuels) could not be used with a Space-based Power Grid without losing any policy-driven financial incentives, which would seriously damage the financials for the earlier years of a space power business.

Space Elevator Power Line. Another idea that has only come up once or twice to my knowledge is that of placing an SPS at the far-end of a Space Elevator, and then transmitting the generated solar power down the cable to the ground. Unfortunately, using the cable of the Elevator for power transmission would require operations at very high voltages (as we discussed before), and such a system would be very vulnerable to electric discharges (i.e., local arcing), which could readily destroy the cable. Moreover, if a Space Elevator for access to space from Earth is ever successfully developed, it could be used to deploy vast amounts of equipment to GEO (and beyond) at low cost – including more conventional SPS systems hardware.

I'm sure there are more Space Solar Power concepts that don't work technically or economically that could also be discussed here; suffice it to say that generally speaking, the types of SSP concepts that we have reviewed in this Chapter are those that appear the most promising given what we know about the technologies that are available, or might become available in the coming decades.

Evaluation of Feasible Concepts

The several SPS concepts described previously are all technically possible; however, they vary greatly in terms of their prospects for economic performance, and in the technological difficulties that they present. The 2008-2001 International Academy of Astronautics (IAA) study described in Chapter 3 analyzed three types of SPS architecture in terms of a number of criteria. Based on that group's analyses, the IAA formulated a summary – albeit highly qualitative – assessment of the three SPS types. This assessment involved two basic considerations: (1) a range of technical criteria (reflecting the policy issues, technology assessment, and systems analyses presented in the preceding chapters); and (2) evaluation versus the four Academy-defined "global scenarios" for how energy/environmental considerations may evolve during the remainder of this century.

In the discussion that follows, the approach used by the IAA is enhanced and extended. Here I have chosen to consider SPS concepts in terms of two major factors, and several important criteria with each; including:

Systems-related criteria, including:

- End-to-end efficiency,
- Utilization of fixed capacity,
- Initial program characteristics (from beginning of R&D to the start of sales)
    - Schedule
    - Funding
    - Technology Readiness and Risk Assessment (TRRA)

External Criteria, including

- Economic Potential

        - Markets on Earth
        - Markets in Space
    - Policy and Regulatory Issues
    - Weaponization Potential
    - Potential Impact on Climate Change

For each of the criteria, a score has been assigned ranging from 1 to 5; where a score of “1” corresponds to the best possible satisfaction of the criteria and a score of “5” corresponds to the worst possible satisfaction of the criteria. The systems-related criteria are defined as follows:[14]

End-to-End Efficiency. This technical criterion takes into account the complete “energy chain” from sunlight incoming to a solar power generation subsystem to the SPS, through the WPT system, to a receiver on Earth. (In these terms, “100% efficiency” – which is impossible – would be perfect.)

Utilization of Fixed Capacity. This criterion concerns the degree to which space and ground segments will be operational during each day. (In this case, constant delivery of power – “24/7” – would be perfect.)

Initial Program Characteristics - Funding. This criterion refers to the expected scope of the funding necessary to implemented R&D, system development, manufacturing, and deployment to the point at which power begins to be delivered. (In this instance, smaller costs are better.)

Initial Program Characteristics - Schedule. This programmatic criterion has to do with the expected time required to accomplish R&D, system development, manufacturing, and deployment to the point at which power begins to be delivered. (In this instance, shorter times are better.)

Initial Program Characteristics - TRRA. This last system-oriented program criterion has to do with the technologies to be incorporated into a given concept, as evaluated in a consistent Technology Readiness and Risk Assessment (TRRA) and, in particular, the technology readiness to begin development, and the riskiness of the R&D program that will be required.[15] (In this case, higher readiness and lower risk are better.)

Similarly, the external factors-related criteria are defined as follows:

Economic Potential – Markets on Earth. This external factor pertains to the market potential of the SPS platform to deliver energy profitably to markets on Earth. (In this case, greater market access is better.) This topic is introduced in Chapter 2, and is discussed in detail in Chapter 11 for the case of the SPS-ALPHA concept.

Economic Potential – Markets in Space. This external criterion has to do with the market potential of the SPS platform systems and technologies for use in space, including but not limited to delivery of energy. (In this case, greater market access is better.) This topic is discussed in detail in Chapter 10 for the case of the SPS-ALPHA concept.

Policy and Regulatory Issues. This criterion has to do with expected policy and regulatory issues – including health and safety risks, spectrum allocation issues, etc. – that may arise in the context of a given SPS system concept. (For this criterion, the fewer the potential issues, the better; this is discussed in Chapter 9.)

Weaponization Potential. This external factors criterion (also discussed in Chapter 9) addresses the potential risk that the SPS architecture (technologies, platform systems, supporting infrastructure, etc.) might be "weaponized" – i.e., used deliberately to harm people or property. (In this case, the less the potential, the better.)

Potential Impact on Climate Change. This final external factor concerns the degree to which the SPS concept may contribute to accomplishing government policy goals vis-à-vis climate change; i.e., the net positive net contribution to resolving these issues. This bears directly on whether the concept may be eligible for policy-driven economic incentives – e.g., tax credits, R&D funding, etc. (In this case, greater impact is preferred.)

A Caveat. Of course, given the high level of uncertainty at present, this evaluation should be regarded as strictly preliminary. As noted elsewhere, more in-depth end-to-end systems analysis studies (supported by relevant technology R&D and demonstrations) are needed.

Evaluation Results. The overall results of the evaluation are presented below. Table 4-2 summarizes a technical comparison of the SPS concepts in terms of the systems criteria, while Table 4-3 provides a comparison among the several types of SPS and individual concepts based on the external criteria.

Evaluation Summary

Based on the two evaluations presented above, an overall evaluation of the several types and specific cases of SPS systems concepts was developed, as shown in the tables. Each evaluation resulted in a weighted average score (each criteria for each concept). Figure 4-27 summarizes the evaluation by SPS type. The highly modular microwave WPT sandwich SPS concepts appear the most attractive, with SPS-ALPHA the overall best.

Table 4-2 Trade Space of SPS Concept Options: Systems-Related Factors

	END-TO-END EFFICIENCY	UTILIZATION OF FIXED CAPACITY	INITIAL PROGRAM			AVERAGE SCORE
Type I			SCHEDULE	FUNDS	TRRA	2.9
(**1A**) 1979 SPS System	1	1	4	5	5	3.2
(**1B**) Solar Disc	1	1	3	3	5	2.6
Type II			SCHEDULE	FUNDS	TRRA	2.5
(**2A**) Abacus Reflector	2	1	3	3	5	2.8
(**2B**) Integrated Symm. Concentrator (ISC)	1	1	3	3	3	2.2
Type III			SCHEDULE	FUNDS	TRRA	2.3
(**3A**) SunTower LEO	1	4	2	2	3	2.4
(**3B**) SunTower GEO	1	2	2	3	3	2.2
Type IV			SCHEDULE	FUNDS	TRRA	1.4
(**4A**) Standard Sandwich SPS	1	1	2	1	2	1.4
(**4B**) Integrated Modular Sandwich	1	1	2	1	2	1.4
Type V			SCHEDULE	FUNDS	TRRA	1.2
(**5**) SPS-ALPHA	1	1	1	1	2	1.2

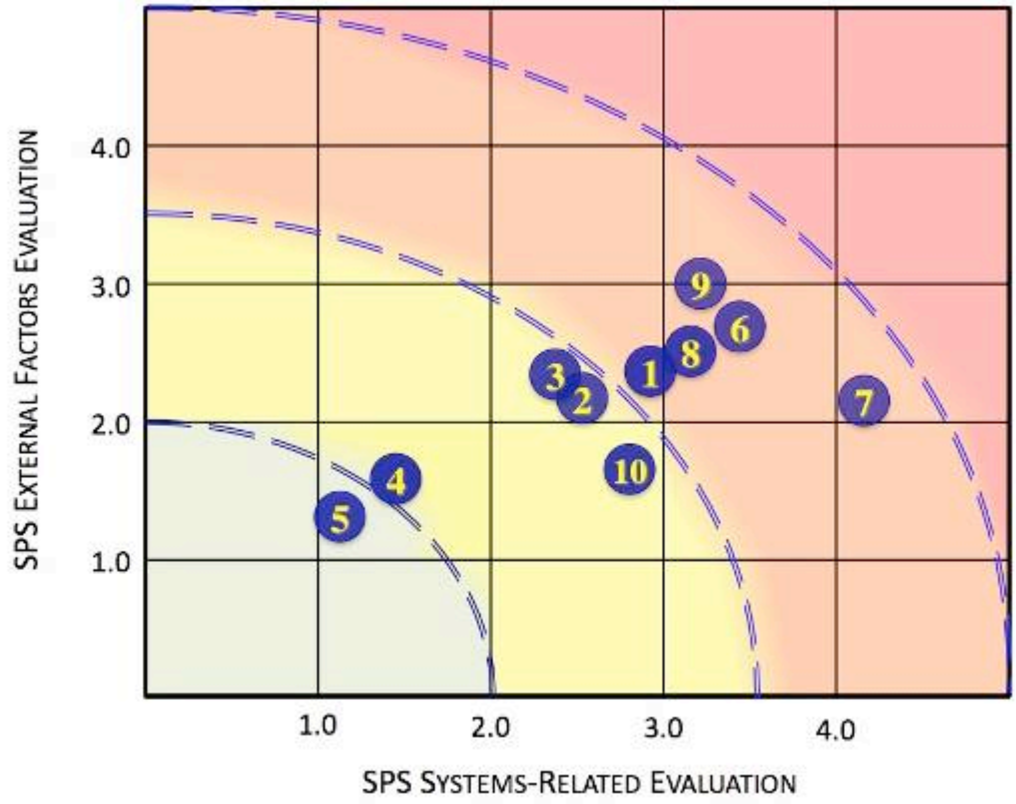
Type VI			**SCHEDULE**	**FUNDS**	**TRRA**	3.4
(**6A**) Modular Laser	4	3	2	3	2	2.8
(**6B**) mm-Wave / Laser SPS with Relay	3	2	4	4	4	3.4
(**6C**) Solar-Pumped Laser	4	3	4	5	5	4.2
Others			**SCHEDULE**	**FUNDS**	**TRRA**	N/A
(**7**) Lunar Solar Power	2	4	5	5	5	4.2
(**8**) Libration Point SPS	2	2	4	5	2	3.2
(**9**) Space-Based Mirror	1	4	3	3	4	3.2
(**10**) Microwave Swarm	5	5	1	1	1	2.8
Demo Concepts	N/A	N/A	1	1	1	N/A

Table 4-3 Trade Space of SPS Concept Options: External Factors

	MARKET POTENTIAL		ISSUES: POLICY OR REGULATORY	WEAPONIZATION RISK	CLIMATE IMPACT	AVERAGE SCORE
Type I	EARTH	SPACE				2.3
(**1A**) 1979 SPS System	3	4	2	1	2	2.4
(**1B**) Solar Disc	2	4	2	1	2	2.2
Type II	EARTH	SPACE				2.2
(**2A**) Abacus Reflector	3	4	2	1	2	2.4
(**2B**) Integrated Symm. Concentrator (ISC)	2	3	2	1	2	2.0
Type III	EARTH	SPACE				2.3
(**3A**) SunTower LEO	4	3	2	1	3	2.6
(**3B**) SunTower GEO	2	3	2	1	2	2.0
Type IV	EARTH	SPACE				1.6
(**4A**) Standard Sandwich SPS	2	2	2	1	1	1.6
(**4B**) Integrated Modular Sandwich	2	2	2	1	1	1.6
Type V	EARTH	SPACE				1.4
(**5**) SPS-ALPHA	2	1	2	1	1	1.4

Type VI	**EARTH**	**SPACE**				2.7
(**6A**) Modular Laser	1	2	4	5	2	2.8
(**6B**) mm-Wave / Laser SPS with Relay	2	2	2	4	1	2.2
(**6C**) Solar-Pumped Laser	1	4	4	5	2	3.2
Others	**EARTH**	**SPACE**				N/A
(**7**) Lunar Solar Power	2	4	3	1	1	1.8
(**8**) Libration Point SPS	3	2	3	1	2	2.4
(**9**) Space-Based Mirror	3	5	2	1	4	3.0
(**10**) Microwave Swarm	1	2	2	1	2	1.6
Demo Concepts	N/A	N/A	1	1	N/A	TBD

Figure 4-27 Integrated Results of SPS Evaluation by Type



LEGEND:

1: Microwave WPT Systems; Electrical PMAD Interconnects; Monolithic Architecture; and, Large, Platform-Level Gimbaled Systems

2: Microwave WPT Systems; Reflector-Based Interconnects, Electrical PMAD; Monolithic Architecture; and, Large, Platform-Level Gimbaled Systems

3: Microwave WPT Systems; Electrical PMAD Interconnects; Modular Architecture; and, Smaller, Locally Gimbaled Systems

4: Microwave WPT Systems; Reflecting Interconnects; Modular Architecture; and, Large, Platform-Level Gimbaled Systems

5: Microwave WPT Systems; Reflectors as Interconnects; Hyper-Modular Architecture; Power Management; and Small, Local-Level Gimbaled Systems

6: High-Frequency WPT Systems; Typically Electrical, but Varying as Interconnects; Typically Modular, but sometimes Monolithic Architecture; and Typically Platform-Level, but sometimes Local Gimbaled Systems

7: Lunar Solar Power

8: Libration Point SPS

9: Space-Based Mirror

10: Microwave Swarm

Credit: Artemis Innovation Management Solutions LLC (2013)

Concluding Observations

It is important to understand the high-level issues that constrain SPS/SSP design choices in general, and to look carefully at different systems types in light of these issues. These issues included (a) key drivers and constraints based on the physics of the systems; (b) selected critical technology issues; and (c) parametric cost considerations.

There are a diverse number of other concepts for space solar power, including alternatives types of SPS platforms and alternative deployment locations. Many of these options were identified in the 1995-1997 NASA SSP "Fresh Look Study," the purpose of which was to determine whether new technologies (emerging since the 1970s) might make possible new, more affordable, SPS systems concepts.[16,17]

The resolution of a number of systems-technology issues is critical to the future economical viability of SSP. The top ten challenges that must be addressed successfully include the following:

Frequency Selection and Atmospheric Interactions
WPT end-to-end efficiency and Transmitter / Receiver Diameters
WPT Beam Intensity at Receiver
Solar Power Generation (SPG) / Power Management and Distribution Specific Mass
Thermal Management System (TMS) mass-effectiveness
WPT Beam Generation Device Selection and Transmitter Rigidity
SPS Platform and Supporting Infrastructure Mass per Unit Power Transmitted/Received
ETO Launch Vehicle – Lift Capacity and Expendability
In-Space Transportation – Utilization of Fixed Capacity
Platform and Operations Autonomy

The First International Assessment of Space Solar Power, completed by the International Academy of Astronautics (IAA) in 2011, found that modular microwave SPS concepts (delivering relatively low power transmission intensity) were the most promising. The more detailed evaluation presented here, addressing some sixteen concepts across multiple basic types, comes to the same conclusion; of the modular microwave WPT concepts, the new SPS-ALPHA approach seems the most attractive.

This discussion makes clear that there really are a great many ways that one *might* attempt to pursue the vision of the Solar Power Satellite. However, many of these concepts are extremely difficult, others are likely to be extraordinarily expensive, and still others just won't work at all.

SPS-ALPHA is a promising new approach derived from the family of sandwich-type microwave power transmission concepts, and based on the idea of hyper-modularity. The next Chapter will present SPS-ALPHA in considerably more detail, based on the results of the 2011-2012 Phase 1 study of this new approach to Space Solar Power sponsored by NASA Innovative Advanced Concepts (NIAC) program.

[4-1] These quotations, like the one from Lee DeForest above, are drawn from various on-line sources, such as: http://www.wikidbs.com/quotes/incorrect-predictions-quotes/.

[4-2] The factor of "2.44" in the equation in Figure 4-2 is a result of the details of the physics; it indicates that about 96%-97% of the energy in the coherent EM beam will fall inside the outer edge of the receiver (i.e., inside D_{Rcvr}).

[4-3] More on antenna and RF engineering can be found in various texts; see for example: Chang, Kai, "*RF and Microwave Wireless Systems*," (John Wiley & Sons, Inc., New York, New York). 2000; or on-line see: http://en.wikipedia.org/wiki/Side_lobe.

[4-4] There are two basic units of measure that may be used interchangeably for EM waves: the *frequency* of the wave and the *wavelength*; they are inversely related to one another, times a universal conversion factor, the speed of light (i.e., "c"), with a value of 300,000 kilometers per second. The *frequency* is in units of "Hertz", which is 1 cycle per second; so 1 GHz is a frequency of 1,000,000,000 Hertz, or 1 billion cycles per second. The *wavelength* that corresponds to 1 GHz is simply:

Wavelength = c / Frequency = (300,000,000 meters/second) /1,000,000,000 / second = 0.3 meters

Both of these units – Frequency and Wavelength – are used throughout this text and the general literature.

[4-5] For additional information, see: http://en.wikipedia.org/wiki/Stefan%E2%80%93Boltzmann_law.

[4-6] The recently-completed (2011) International Academy of Astronautics (IAA) assessment considered three basic types of SPS: monolithic microwave WPT systems; modular laser WPT systems; and modular microwave WPT systems. This taxonomy is encompassed by the discussion developed here, which also considers a much more "granular" breakdown of the system design issues involved.

[4-7] The details of how NASA and many other aerospace and advanced technology R&D organizations assess technology maturity – the Technology Readiness Levels – are discussed in Chapter 14.

[4-8] National Research Council, Aeronautics and Space Engineering Board, Committee for the Assessment of NASA's Space Solar Power Investment Strategy, Aeronautics and Space Engineering Board, "Laying the Foundation for Space Solar Power: An Assessment of NASA's Space Solar Power Investment Strategy." (National Academies Press; Washington, D.C. USA). 2001.

[4-9] While at NASA, I created the SunTower as part of the US "Fresh Look Study." See: Mankins, John C., "A Technical Overview Of The 'SunTower' Solar Power Satellite Concept" (IAF-97-R.2.08; 38th International Astronautical Federation, Turin, Italy) 6-10 October 1997. Although there had been long, gravity-gradient, stabilized concepts proposed earlier (for example, by SAIC at the end of the SPS studies of the 1970s), these were largely unknown by the mid-1990s.

[4-10] There are, of course, many more SPS concepts that might be discussed. The set presented here is that which appears – in my view – to be the major "lines of attack" on the challenge of Space Solar Power.

[4-11] Criswell, David R., "Power Collection and Transmission System and Method" (US Patent No. 3,781,647; U.S. Patent and Trademark Office; Washington, D.C.) 28 May 1991.

[4-12] The overall terrestrial market context was described in Chapter 2; details of that market and the potential in-space market for SPS-ALPHA in particular are discussed later.

[4-13] See: http://en.wikipedia.org/wiki/The_Caves_of_Steel

[4-14] You may wonder why the key technical figures of merit (for example, the "Specific Power" – i.e., the power delivered per unit mass of platform) are not included in this discussion. This is the case because generally speaking these data are not available. There has been no internally consistent systems analysis study of multiple SPS systems concepts since the Fresh Look Study in the mid-1990s. The evaluation here is admittedly qualitative for that reason, and relies on information from various sources about the architectures evaluated.

[4-15] This topic is discussed in much greater detail for the SPS-ALPHA concept in Chapter 5. The results presented here follow on the results of the previously cited IAA study, expanded to encompass the additional SPS concepts. The overall methodology for Technology Readiness and Risk Assessments (TRRAs) is described in Chapter 15.

[4-16] Mankins, John C., "Space Solar Power: A Fresh Look," AIAA 95-3653 (Presented at the 1995 AIAA Space Programs and Technologies Conference, Huntsville, Alabama). September 1995.

[4-17] Feingold, Harvey, et al, "Space Solar Power — A Fresh Look at the Feasibility of Generating Solar Power in Space for Use on Earth" (SAIC; Schaumberg, Illinois, USA). 02 April 1997.

Chapter 5

SPS-ALPHA:

A Practical Approach to Space Solar Power

"The best victory is when the opponent surrenders of its own accord before there are any actual hostilities...It is best to win without fighting."

Sun Tzu (~ 400 BC)
The Art of War (Planning a Siege)

Introduction

As we've discussed, the concept of the Solar Power Satellite (SPS) has a history that goes back almost to the beginnings of the space age; the idea of collecting and using solar energy in space is even older.[1] So, if Space Solar Power (SSP) is such a good idea, why hasn't it already been accomplished? In the last Chapter, we reviewed both the most important physical constraints that must be dealt with and a number of different architectural approaches that have been suggested. In my view, the engineering efficiency of a particular SPS approach is only a part of the story – and not necessarily the most important part. To find an answer, we must examine a mixture of the engineering, economic, programmatic, and policy (e.g., regulatory) considerations that come into play.

As we saw at the end of Chapter 4, when all of these aspects are taken into account, the least promising options are those that involve large, monolithic systems, those involving high frequency wireless power transmission (WPT) such as lasers, and options that require substantial up-front infrastructure investments. The most promising are those options that are highly modular, use microwave WPT, and require minimal – perhaps no – unique initial infrastructure investments. Moreover, SPS concepts are preferred that promise important initial applications in space exploration, commercial space development and other space objectives.

The mass and cost of platform systems are fundamental drivers for SPS economics – more important even than ETO or in-space transportation because the mass to be transported directly affects both of these. Some of the key cost contributors (i.e., Figures of Merit, or "FOMs") for the SPS platform itself include the following:

- Manufactured Cost per SPS Platform Hardware Unit Mass ($/kg)
- SPS Platform Hardware Unit Mass per Unit Power Delivery Capacity (kg/kW)
- Solar Power Generation Power per unit Mass (W/kg)

- Annual Fractional Expendability per SPS Platform unit Mass (% of SPS Mass /Year)
- Number of Modules per SPS (Number)
- SPS Hardware Manufacturing Learning Curve (H/W cost reduction per doubling of Manufactured Unit; $/Doubling))
- SPS Platform Assembly Cost per SPS Platform Hardware Unit Mass ($/kg)

The contribution to the cost per kilowatt-hour due to the SPS hardware manufactured cost is a straightforward calculation based on the FOMs identified above. The most promising architectural approach to achieving much lower hardware costs is through "hyper-modularity," i.e., implementing an overall system by means of a large number of physically integrated smaller systems. SPS-ALPHA, the new architectural approach introduced late in the preceding chapter, is the most recent (and in my view the best so far) in this most promising line of attack on the challenge of Space Solar Power.

The following discussion sets the stage for the central argument of this book: that Space Solar Power can be both technically feasible and realized in an economically viable and programmatically achievable way. The rest of this Chapter, and portions of the next several, will describe the hyper-modular architecture and explain how it solves the principal challenges of SPS.

SPS-ALPHA Concept Overview

The basic concept of SPS-ALPHA is to form an exceptionally large space platform from an extremely large number of small, highly modular elements, using a minimum number of module types. A colony of ants cooperate to reach their objective, bees work together in build and feed their hive, and a team of skydivers must cooperate to form quickly a large, complex structure during a jump. In the first two instances, there are even tailored body types to perform specialized functions – drones, soldiers, and so on. Figure 5-1 illustrates these examples of cooperative behavior. In the case of SPS-ALPHA, the modular elements (of which eight basic types have been defined so far) will be combined in various ways to comprise a number of functional assemblies, which in turn make up the full SPS platform. (In addition, the eight module types can be combined to assemble other types of spacecraft – as is described in Chapter 11.)

Figure 5-1 Examples of Cooperative Behavior: Ants, Bees and Sky Divers

Comparison with Traditional Architectures

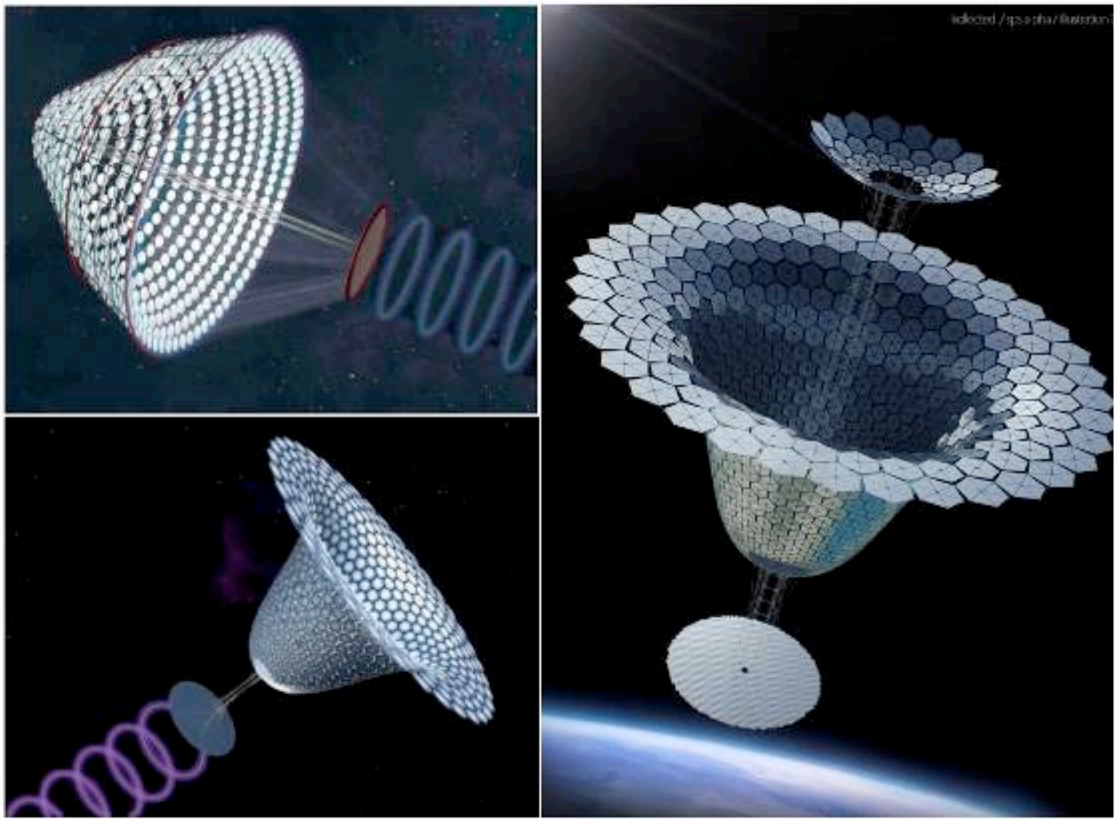
Traditional space systems reflect an architectural approach that may be described as integrated or monolithic.[2] In other words, the mission objectives (whether they are scientific, military or commercial) are accomplished by a single system or system of systems in which there are no more than one or a small number of identical elements. Examples range from launch vehicles to various Earth-orbiting satellites to deep space robotic missions and human space exploration systems. These include systems starting with the first satellites in the earliest days of the space program in the 1950s, and continuing with the systems of the Apollo Program in the 1960s, the Space Shuttle in the 1970s (which had three identical main engines (SSMEs), but represented a single system), the Cassini spacecraft to Saturn in the 1980s-1990s (with its Huygens probe that was dropped on Saturn's moon Titan), and the International Space Station (ISS). The ISS was constructed during multiple missions, but still represents a single large system albeit with a number of identical elements, such as the solar arrays. Most Earth-orbiting satellites have a main body (called a satellite "bus") with a payload pointed toward a target on Earth (for example, a region needing communications services), and one or more photovoltaic

(PV) arrays that point toward the sun and provide power for the payload. And, between the spacecraft bus and the PV arrays that point toward the sun, is a rotating electrical connection.

There are a number of space programs that require multiple space systems to accomplish overall program goals and objectives. For example, the Global Positioning Satellite (GPS) system requires multiple satellites operating in orbit simultaneously to accomplish the goal of assured position, location and navigation services to civil, commercial and military operations on Earth. Similarly, the Iridium Constellation requires multiple satellites operating (and communicating satellite-to-satellite) in low Earth orbit (LEO) to provide global coverage to government and private sector customers on Earth. However, the individual satellites that comprise these constellations are integrated or "monolithic" architecture systems.

By comparison, SPS-ALPHA would not be a traditional 3-axis stabilized satellite with one or more solar arrays (aka, "solar paddles" as described in Japan). Rather, SPS-ALPHA would entail body-mounted, non-moving, solar power generation (SPG) systems on a gravity-gradient stabilized satellite, with an axi-symmetric physical configuration. The SPS-ALPHA concept would typically involve three major functional elements: (1) a large, primary WPT transmitter array that is nadir pointing (i.e., pointed toward Earth); (2) a very large, sunlight-intercepting reflector system (involving a large number of reflectors that act as individually pointing "heliostats," mounted on a non-moving structure); and (3) a truss structure that connects those two. There are several different geometries that might be used; Later in this Chapter, Figure 5-14 presents the silhouettes of several alternatives configurations. Optimization remains for the future, and will depend upon the specific orbit of the SPS platform and market to be served. Figure 5-2a presents several alternative configurations of the SPS-ALPHA architecture. Figure 5-2b presents another set of alternatives: potential sites where the wireless power receiver might be placed on Earth – including sites above green fields, in the desert, or at sea.

Figure 5-2a High-Level Illustration of Alternative Versions of SPS-ALPHA



As we discussed in Chapter 4, SPS concepts of the late 1960s and 1970s followed a common architectural approach. As proposed, these SPS would have been assembled in space (like the ISS), but would have been huge, monolithic systems. For example, the classic 1979 SPS Reference System was a colossal 3-axis stabilized integrated space system with a single sun-pointed solar array. It was about 5 km by 10 km (or larger) and had a rotary gimbal system that transferred power to a large number of electron tube based microwave generating systems (for example, via Klystrons). These generating systems, in turn, fed RF energy into a mechanically rigid 1,000 meter diameter Earth-pointing microwave waveguide antenna system. Truly stupendous in concept, the 1979 SPS architecture would have been a single, monolithic 50,000 MT-100,000 MT space system.

Figure 5-2b Alternative Ground Receiver Placement for SPS-ALPHA Wireless Power

As mentioned (and described in greater detail later in this Chapter), SPS-ALPHA represents a radically different approach; it is a biologically inspired architecture that has more in common with a hive of bees or a colony of ants than to traditional satellites. Here, a very large number of modules would be assembled to form a single enormous satellite. Certainly this architecture cannot be accomplished without the use of several emerging technologies, as well as the application of various existing space technologies used in new ways.[3] However, no breakthroughs in physics or materials are required.

Technological Foundations of the Concept

SPS-ALPHA cannot be accomplished using the standard "quiver" of technical "arrows" used in traditional space system designs. The engineering foundations of this new architectural concept include the following elements.

Retro-Directive Phased Array. The SPS-ALPHA concept depends on a key technological innovation that occurred in the late 1980s: the retro-directive phased array. This technology allows a large number of individual RF elements to be controlled and their transmissions made coherent through the use of a "pilot signal" transmitted from the site of the planned receiver. In other words, in much same way that the conductor and his baton brings the members of an orchestra into synchronicity, by receiving a common reference signal from the ground a retro-directive phased array can employ a great many small transmitters that are brought into phase independently. This technology, which was co-invented by Prof. Nobuyuki Kaya of Kobe University (of whom we have spoken before), allows the large microwave WPT transmitter required for SPS-ALPHA to be assembled from many modular elements. Moreover, because each element can adjust for any local distortions in the shape of the transmitter, the WPT system does not have to be rigid and can be extremely lightweight. Through the use of retro-directive phase control, the transmitter can be low mass and rather flexible and still send power to the receiver on Earth with precision. This technology has already been tested at low TRL in the field, including tests in Hawaii (in 2008 and 2010) and a demonstration at the international SPS 2009 symposium and conference in Toronto, Canada (September 2009).

Large/Individually-Pointed Thin-Film Reflectors on a Non-Rotating Structure. Rather than conventional solar arrays, SPS-ALPHA will instead use a unique, large, thin-film reflector configuration to redirect and concentrate sunlight onto PV arrays that are integrated with the primary transmitter array; this is illustrated in Figure 5-2a. The reflectors are capable of providing almost constant solar energy to the transmitter modules (described below), and there is no single-point-of-failure gimbaled system, as there are in many other SPS concepts. This approach closely mirrors the sunlight harvesting approach used in very large ground-based Concentrator Solar Power (CSP) power plants, such as Spain's *Solucar PS10* and the Ivanpah Dry Lake power plant in California.[4] In these plants, the reflectors that point constantly and redirect sunlight to a central tower are called "heliostats." SPS-ALPHA proposes to use a heliostat approach in which the reflectors are mounted on a non-moving structural framework, and each of which is an extremely large, thin film mirror that are only possible in the zero gravity of space.

Significant advances have been made in the field of space reflectors in the past decade, primarily for use in propellant-less propulsion by means of solar sails (that would use the pressure of sunlight to move a lightweight spacecraft). A recent notable accomplishment was the successful launch and deployment of Japan's IKAROS solar sail demonstration in 2010.[5] Prototypes and tests on the ground have also been accomplished in the US and at DLR (the German aerospace center).

Robotic Assembly in Highly Structured Space Environments. The hyper-modular SPS-ALPHA architecture depends on in-space robotic assembly at an unprecedented scale. However, the requirement is for robotic assembly in a highly structured environment – not an unstructured environment such as that found in planetary surface exploration. (There are no boulders, hills, cliffs or canyons in GEO!) The type of technology needed is currently in use in terrestrial applications such as automated mining operations, large-scale commercial farming, or automated warehousing. However, SPS-ALPHA is unique in that novel combinations of the standard eight modular elements rather than using stand-alone systems will perform all needed robotic operations.

There has already been tremendous progress in the relevant technologies, both by NASA (see the ATHLETE rover concept of the Jet Propulsion Laboratory, developed by Brian Wilcox and his team with guidance by Dr. Neville Marzwell), Prof. David Miller's beautiful cooperating free-flying "SPHERES" robots of the Massachusetts Institute of Technology (MIT), and the remarkable European miniature helicopter structural assembly demonstration by Flight Assembled Architecture Centre (FRAC) in France.[6]

Mass Production (at Low Cost) of All Platform Elements. The potential economic viability of SPS-ALPHA depends on mass-producing all elements of the system. The highly modular architecture should certainly allow the use of manufacturing analogous to that currently used for satellites in large constellations (such as the Iridium), or in the manufacture of mass-produced aerospace systems such as Remotely Piloted Vehicles with hardware costs less than $500-$1,000 per kg. However, SPS-ALPHA must go still further to enable production runs and costs comparable to those of high-technology consumer products – such as personal computers, PV arrays, etc.

These items really define the SPS-ALPHA architecture; in addition, there are obviously a variety of additional needed technologies – some of them vitally important – such as high-efficiency PV cells, high-temperature electronics, low-mass structures, and others. These are discussed further in Chapter 13 as part of the technology readiness and risk assessment (TRRA). Additional key technical characteristics of the concept include:

Orbital Location. To deliver energy to Earth, SPS-ALPHA would be based in a geosynchronous Earth orbit where it would intercept sunlight (99.5% of the time annually) using a collection of individual thin-film mirrors, convert that sunlight across a large RF aperture into a coherent microwave beam, and transmit it to targets on Earth. SPS-ALPHA might also be based in alternative Earth orbits or elsewhere, such as at Earth-Moon Libration points, lunar orbit, Sun-Earth Libration points, or Mars orbit. It would deliver abundant and affordable solar power not only to Earth but also to enable ambitious future space exploration and development.

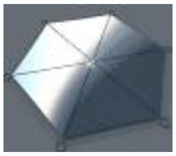
Fault Tolerance. The SPS-ALPHA concept involves no single points of failure and is highly scalable from small prototypes to larger sizes and higher power levels. Each of the intelligent modular elements that comprise the large aperture, the connecting structure, and the reflector systems would incorporate multiple "smallsat" class modules. These modules operate cooperatively but independently; hence, the fault tolerance of the total system is dramatically higher than it would be for any similar sized monolithic system concept.

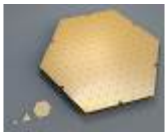
Detailed Description of SPS-ALPHA

Introduction

SPS-ALPHA comprises at this time eight distinct modular elements, each of which may be integrated in various implementations to realize an overall system: (1) the HexBus Module; (2) Interconnects; (3) the HexFrame Structural Module (HSM); (4) the Reflector Deployment Module (RDM); (5) the Solar Power Generation (SPG) Module; (6) the Wireless Power Transmission (WPT) Module; (7) Modular Autonomous Robotic Effectors (MARE); and, (8) the Propulsion / Attitude Control (PAC) Module.[7] Table 5-1 provides a high-level generic summary of these currently identified SPS-ALPHA system elements.[8]

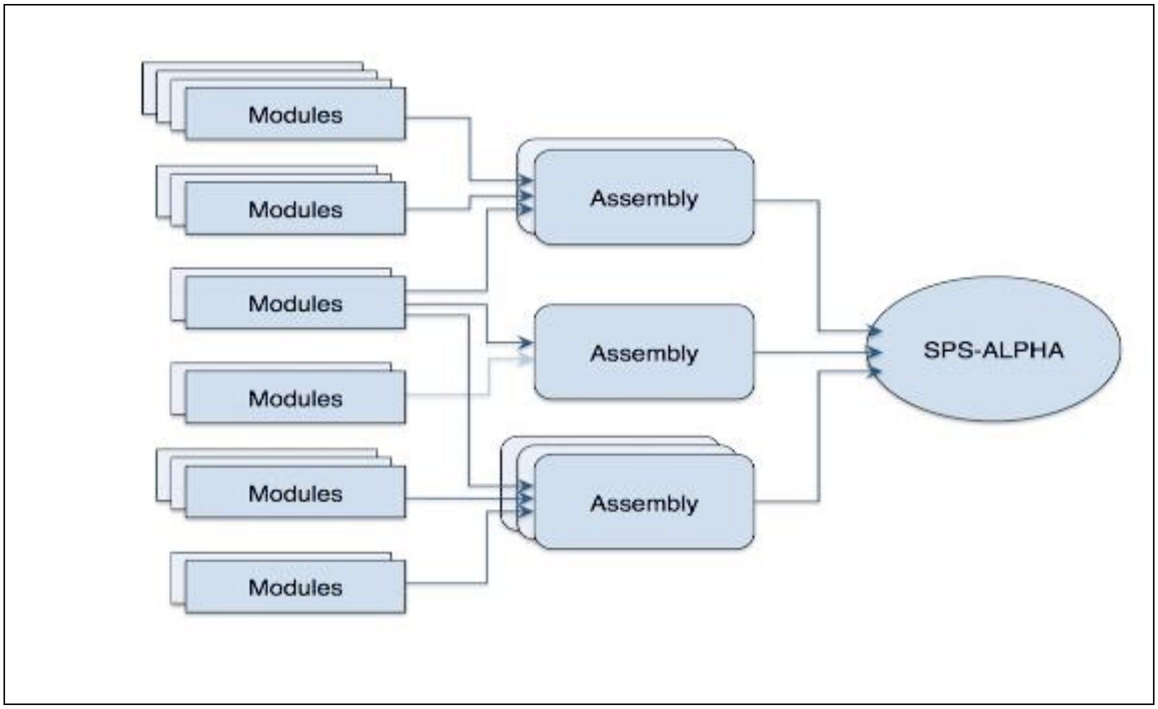
Table 5-1 Summary of Current SPS-ALPHA Generic System Modules

System Modular Element	Description of the Module	Modular Element Illustration	Estimated Mass of Each Module (kg)
HexBus	The "HexBus" is a specially configured "smallsat" capable of wirelessly communicating with neighboring systems. The typical diameter would be about 4 meters, but could change based on the overall size.		~ 25 kg
Interconnects	The "Interconnects" are nanosats that mechanically link essentially all other SPS-ALPHA modules to one another. An "Interconnect" would typically be about 5 cm by 15 cm in size.		~1 kg
HexFrame Structural Module	The "HexFrame Structural Modules" (HSMs) are simple deployable beams (specific type to be determined) that provide the base structure for the reflectors, and connect the reflector array to the power/transmitter array.		~50 kg
Reflector Deployment Module	The "Reflector Deployment Module" (RDM) are large, thin-film reflectors (e.g., aluminum on Kapton) that redirect incoming sunlight to the SPG, along with a central deployment plate.		~75-100 kg
Solar Power Generation (SPG) Modules	The "Solar Power Generation" (SPG) modules generate the power for the WPT transmitter; there are six per HexBus.		~15-20 kg

System Modular Element	Description of the Module	Modular Element Illustration	Estimated Mass of Each Module (kg)
Wireless Power Transmission (WPT) Module	The "Wireless Power Transmission" (WPT) modules convert the electricity on the platform into a coherent RF (microwave) transmission to the receiver on Earth; there is one unit, with numerous sub-elements per HexBus.		~50 kg
Modular Autonomous Robotics Effector (MARE)	The "Modular Autonomous Robotic Effector" (MARE) systems are the "work-horses" of the concept; they provide all sorts of In-Space Assembly and Construction (ISAAC) and actuation onboard the SPS-ALPHA Platform.		~ 10 kg
Propulsion / Attitude Control Module	The "Propulsion / Attitude Control" (PAC) Modules provide the required propulsion for guidance, navigation and control (GN&C) and station keeping for the Platform. (The total mass, including the tank size, will depend on time between refueling.)		50-500 kg**

The overall architecture of SPS-ALPHA assumed the initial integration of the eight individual modules into a handful of "Assemblies," each involving two or more of the modules. These Assemblies would then be integrated into major systems and the overall SPS platform. Figure 5-3 presents a conceptual illustration of this hierarchical approach.

Figure 5-3 SPS-ALPHA Module-Assembly-System Architecture



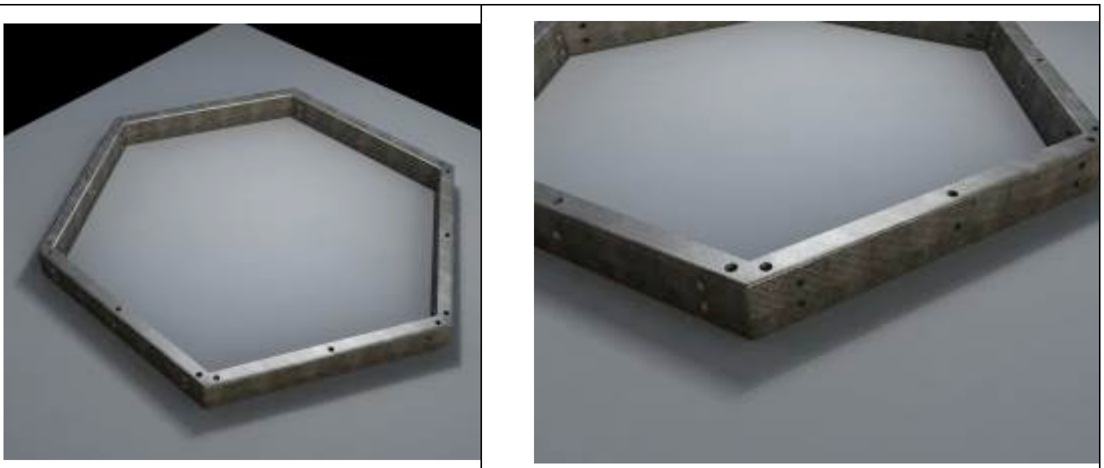
The following paragraphs provide more detailed descriptions of each of the modular elements of the SPS-ALPHA concept; a discussion of the details of the Assemblies (and their integration) follows.

SPS-ALPHA Module Descriptions

HexBus. The "HexBus" is a specially configured smallsat capable of mechanically connecting to, and wirelessly communicating with neighboring systems. The HexBus is conceived of as a "ring structure," with finite height and thickness, in which the center of the structure is open. A single Hexbus could be hexagonal when viewed from the top, or could be of different shapes (e.g., triangle, square, or parallelogram) or combinations of shapes (e.g., square and octagon), so long as the combination allows the "tiling" of a plane to create a large aperture system in space. Figure 5-4 presents a conceptual illustration of this module.

A nominal physical configuration for the HexBus would be one in which the overall "ring" is about 4 meters in diameter (corner to corner), the thickness of the ring is about 15 cm, and the height of the bus is 20 cm. The ring would be hollow, with the interior being reserved (just as is the interior of a CubeSat) for various subsystems, and incorporating needed internal structures.

Figure 5-4 Illustrations of the “HexBus” Modular Spacecraft Concept



HexBus Perspective View

HexBus Close-Up View

However, the dimensions for a HexBus could be adjusted as needed (for example, a demonstration system could be smaller in scale without affecting the principal functionality of the HexBus concept. As shown in the figure, it is anticipated that the HexBus could be fabricated from a number of materials, including aluminum, carbon composites, or more exotic materials such as composites that include a proportion of Carbon Nanotubes (CNTs).

The Interconnects and the MARE Arms (described below) would connect to the Hexbus through one or more of a series of recessed grapple fixtures in the top, bottom, and sides of the bus (these appear as “holes” in Figure 5-4). The following subsystem functions are expected to be incorporated into each HexBus:

- Mechanical and Structural, including unique identifiers such RFID tags, Bar Codes at specific locations on the frame, etc., which are not shown.
- Command and Data Handling
- Power, including a small battery, and a small body-mounted solar array on the surface of the HexBus[9]
- Power Management and Distribution (PMAD), including power wire, switches, control chips, etc.
- Telecommunications (including a wireless router)
- Data Harness

- Guidance Navigation and Control (GN&C) Sensors
- Thermal

Propulsion System Controls & Interfaces [only in the version for the Propulsion / Attitude Control Assembly (PACA), see below]

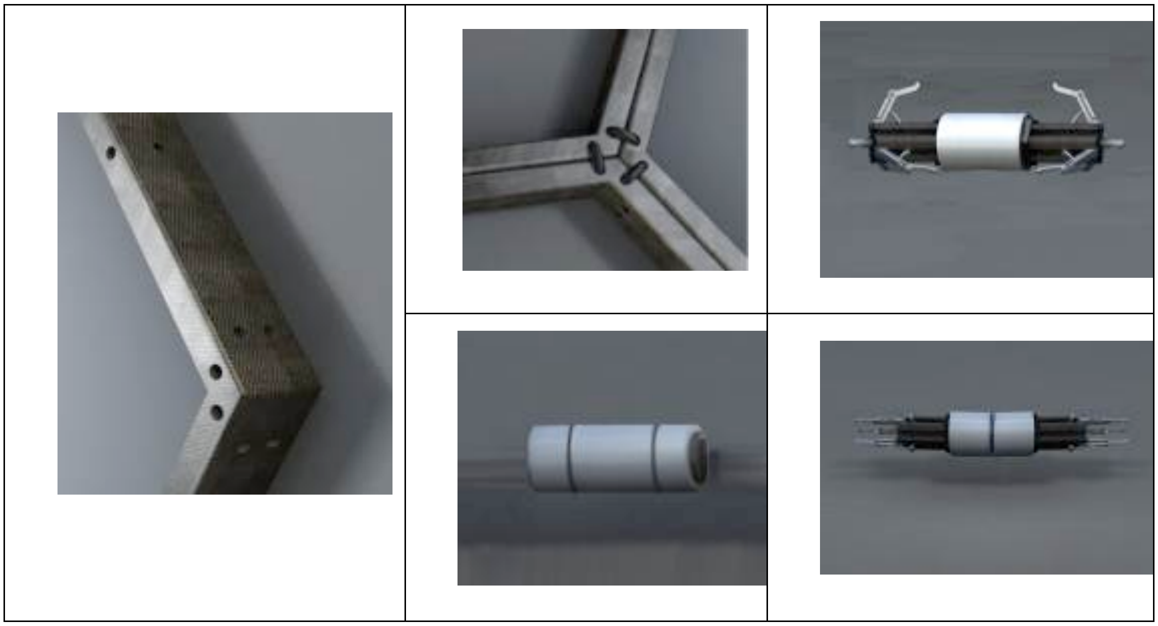
The mass for a given HexBus has been estimated based on its function, as have preliminary masses for all of the modules within the SPS-ALPHA "system of systems;" these mass estimates vary somewhat depending on the specific scale and concept of operations (CONOPS) for the platform.

The diameter of the HexBus structure as well as the height and thickness of the ring are all variables that need to be analyzed in greater detail, as do the choices of materials and positioning of key subsystems inside the ring. Prototyping should play a key role in the resolution of these factors. The potential incorporation of larger-scale power distribution (from HexBus to HexBus) and similar waste heat distribution are also topics for future analysis and R&D.

Interconnects. The "Interconnects" are nanosats (approximately 1 kilogram in mass) that mechanically link almost all other SPS-ALPHA modules to one another (The MARE systems, which can connect directly to the HexBus modules, are exceptions). Figure 5-5 presents several conceptual illustrations of this nano-sat scale connecting module, along with a close-up view of an inset option for the grappling fixture to which the Interconnects would attach when deployed.

The specifics of the Interconnects structure and mechanical actuators, including the width and length of an Interconnect, are all variables to be analyzed in greater detail, as are the choice of materials and details of interfaces with each of the other SPS-ALPHA modules. Prototyping should play a key role in the resolution of these and other issues. At a minimum, the Interconnects must connect various modules to the Hexbus modules (or release them when necessary). They may provide additional functionality, such as vibration isolation (passive or active) when required.

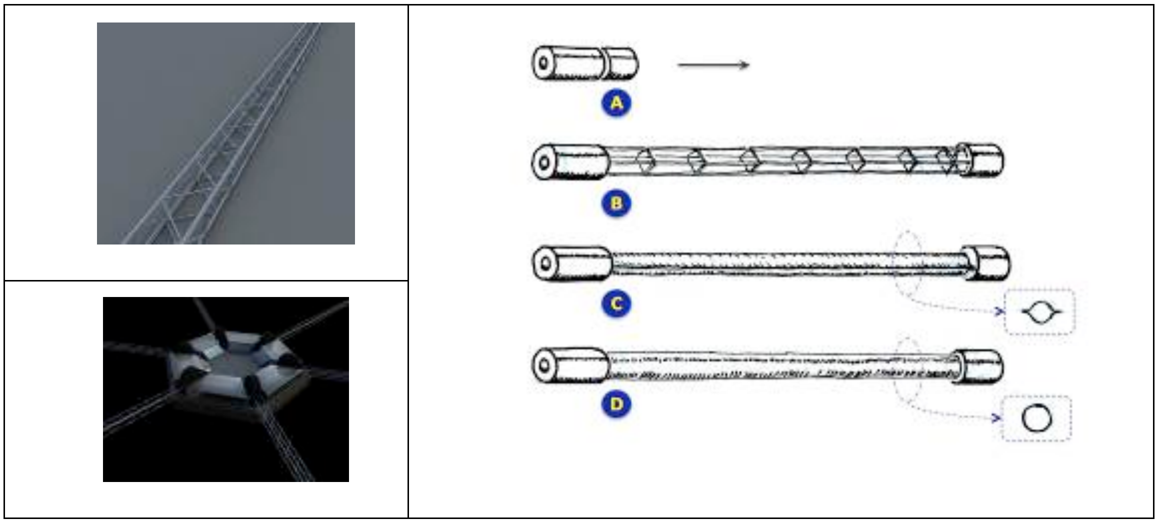
Figure 5-5 Illustrations of the “Interconnects” Concept



HexFrame Structural Module

Each “HexFrame Structural Module” (HSM) is a deployable beam that can also be assembled with other HSMs and Hexbuses to provide the basic structure element of the SPS-ALPHA concept, including the structure for the Solar Reflector Assembly (SRA) and the Connecting Truss Assembly (CTA), both described below, to connect the Solar Reflector Assembly to the Primary Power/Transmitter Array. Figure 5-6 presents a conceptual illustration of this module, including a number of alternative optional approaches.

Figure 5-6 Options for “HexFrame” Structure Deployable / Assembly Beam Concept



In the figure, the “A” tag indicates a not-yet deployed HSM canister; specific dimensions (including the aspect ratio – length to diameter – of the deployed structure) are yet to be determined. At present, there are three HSM options: a deployable truss structure (Tag “B”), a pre-stressed structure (Tag “C”), and an inflatable / rigidizable structure (Tag “D”). In all three of these cases, the HSM integrates with other SPS-ALPHA elements. In addition, the structure is used as a key component in the Reflector Deployment Modules (RDMs), discussed below.

The HSM structures are used in combination with other modules to deploy a variety of key structural parts of the SPS-ALPHA platform. Details of these applications are described below (see Primary Structure Assembly, and Connecting Truss Structure Assembly). These include three basic functional purposes in the SPS-ALPHA concept: (1) to provide (in combination with HexBuses, and Interconnects) the framework upon which the individually pointed “heliostat” reflectors are mounted (i.e, the “Reflector HexFrame”); (2) to provide (in combination with Hexbuses and Connectors) the structure that connects the Reflector HexFrame and the Primary Array; and (3) to create in combination with Hexbuses, Interconnects, Modular Robotic Arms (MAREs), and the Reflector Deployment Modules (RDMs) with reflectors, which are the individually pointed “heliostats.”

The specifics of the type of structure to use for the HexFrame, including the width and length of a single boom as well as the choice of materials and details of interfaces with each of the other

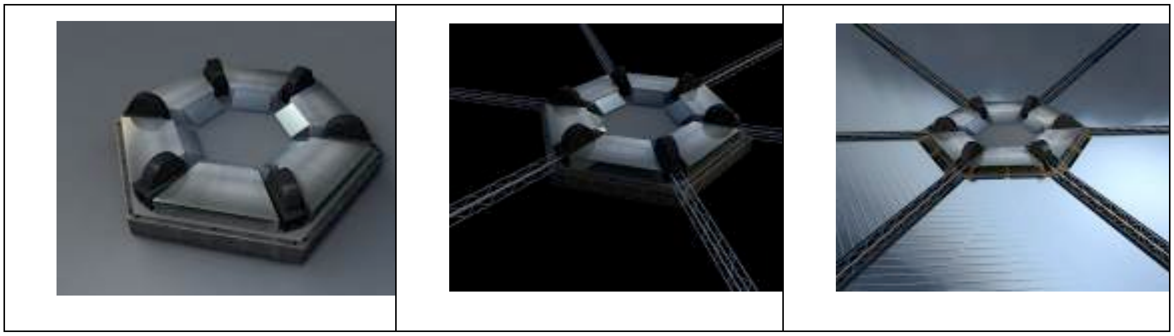
SPS-ALPHA modules, are all variables to be analyzed further. As previously mentioned, prototyping should play a key role in resolving these questions.

Reflector Deployment Module (RDM)

The “Reflector Deployment Module” (RDM) is a specially configured canister in which a number of large, thin-film reflectors (e.g., aluminum on Kapton) are folded and ready for deployment when appropriate. The RDMs are used, when integrated into the Solar Reflector Assembly (SRA), to redirect incoming sunlight to the SPG. In the baseline case as illustrated in this report, the configuration of the basic building block is a hexagon, and so each RDM would have six sides and would deploy some six triangular thin-film reflectors. Figure 5-7 presents a conceptual illustration of this module, including several stages of deployment. (See the discussion of the Solar Reflector Assembly (SRA) for additional information and images.)

The RDM is pre-integrated (prior to launch) with six deployable HexFrame Booms that extend with the thin-film reflectors already attached at the ends of each boom. There is considerable heritage for the RDM concept. (A prototype was tested in the laboratory by DLR in the early 2000s of a four-sided boom-based solar sail concept that is quite similar to the six-sided concept presented here.)

Figure 5-7 Illustrations of the Reflectors Deployment Module (RDM) Concept

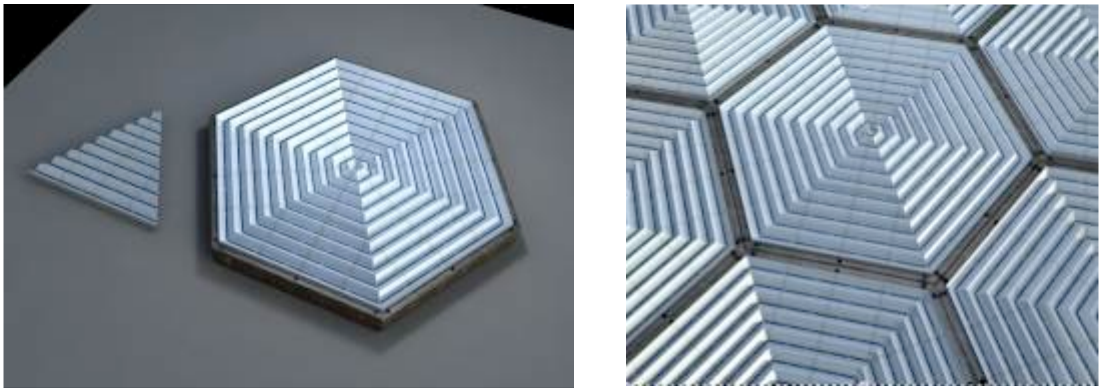


The specifics of the structure and mechanical actuators, including the width and length of an Interconnect, are all variables to be analyzed in greater detail, as are the choice of materials and details of interfaces with each of the other SPS-ALPHA modules. Prototyping should play a key role in the resolution of these and other issues.

Solar Power Generation (SPG) Module

The solar power generation (SPG) modules generate the power for either the WPT module or for the PAC module. Nominally, there are six (6) SPG modules per HexBus in either the Primary Array Assembly of the PAC Assembly (described below). Figure 5-8 presents a conceptual illustration of this module along with a set of SPG modules integrated on a single HexBus. In the left-hand panel, an individual SPB module (the triangle on the left) is shown; on the right side, multiple SPG sets are shown, integrated on the "back-side" (away from Earth) of the Primary Array. The reference approach for the SPG module in a full-scale SPS-ALPHA is to incorporate high efficiency multi-bandgap PV cells.

Figure 5-8 Illustrations of the "Solar Power Generation" (SPG) Concept



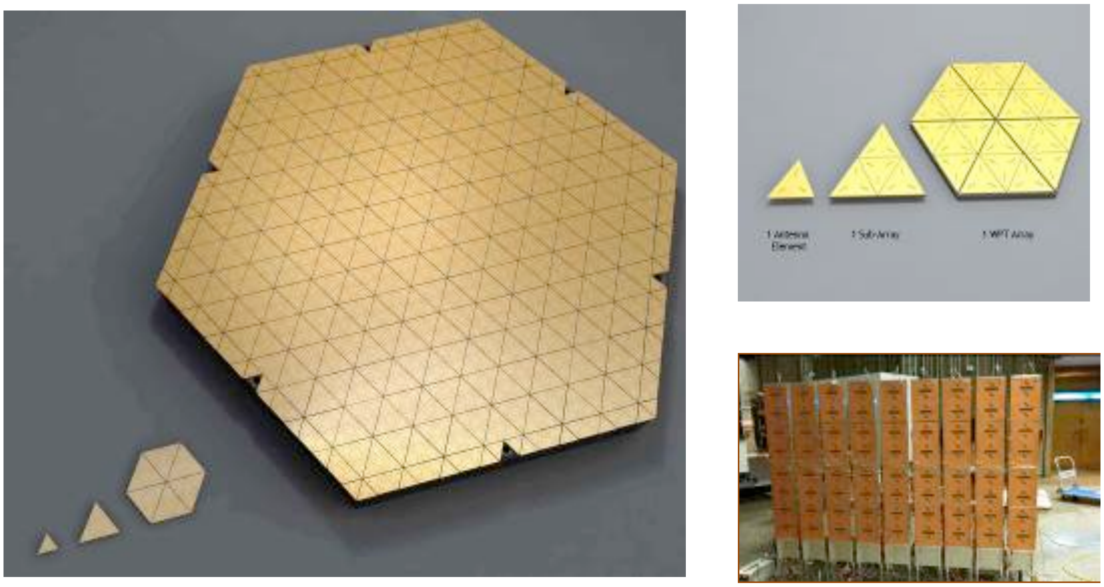
In addition to the specific mass (kg per kW) of the SPG modules, the energy conversion efficiency (photons-to-DC) is also extremely important; the higher the efficiency, the lower the production of waste heat and the lower the temperature of the module for a given level of power production. Early demonstrations of the SPS-ALPHA concept will not require high efficiency and low mass in the SPG; however, these characteristics will be crucial in the full-scale SPS. Further study and prototyping are needed, including technology flight experiments.

Wireless Power Transmission (WPT) Module

The WPT modules convert electricity on the platform into a coherent RF (microwave) transmission to the receiver on Earth; just as with the SPG modules, there are numerous WPT units per HexBus. Figure 5-9 presents a conceptual illustration of this module.[10] The key technology that enables wireless power transmission from a somewhat flexible large aperture (as in SPS-ALPHA) is the retrodirective phased array (RPA), in which a pilot signal sent from the vicinity of the planned receiver on Earth delivers a phase reference to each WPT sub-array (see upper right corner of the figure).

The phase reference signal enables the total system (incorporating some thousands of Primary Array Assemblies) to transmit RF energy coherently to the target. The photograph in the lower right corner of Figure 5-9 is an actual retrodirective phase control microwave WPT transmitter, developed by Prof. Nobuyuki Kaya and his Kobe University team in 2009.

Figure 5-9 Illustration of the “Wireless Power Transmission” (WPT) Module



The SPS-ALPHA planned approach for the WPT module in a full-scale SPS-ALPHA is to employ high power and high efficiency solid-state power amplifiers (SSPAs). In addition to the specific mass (kg per kW) of the WPT modules, the energy conversion efficiency (DC-to-RF) is extremely important; the higher the efficiency, the lower the production of waste heat and the lower the temperature of the module for a given level of power transmission. Additional R&D is needed, addressing SPG components (e.g., PV cells) and modules as well as systems studies and prototyping.

Modular Autonomous Robotic Effector (MARE) Description

The central concept for assembly and servicing of the SPS-ALPHA platform is to utilize a small number of types of Modular Autonomous Robotic Effector (MARE) systems that can be reconfigured in a wide variety of ways. In principal, at least three tailored types of MARE systems will be required: one for servicing and construction operations (including mobility on the platform); another for reflector pointing and placement of the Solar Reflector Assemblies (SRAs) on the passive Primary Structure Assembly; and a third for thruster pointing by the Propulsion and Attitude Control Assembly (PACA). These robotic arms will operate independently or connect to each other and operate cooperatively, or connect to HexBus modules to implement various key functions, including In-Space Assembly and Construction (ISAAC) and Space Assembly, Maintenance and Servicing (SAMS) for the platform. Figure 5-10 presents a conceptual illustration of two views of one configuration for the MARE module.

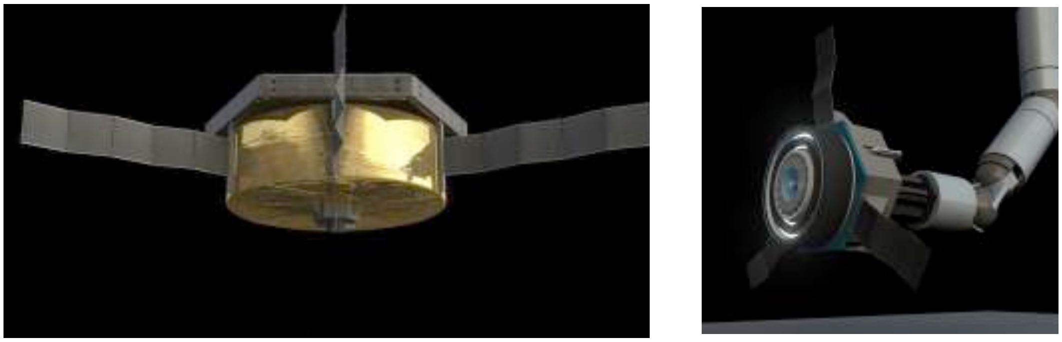
Figure 5-10 The Modular Autonomous Robotic Effector (MARE) Concept

In general, the MAREs benefit from a strong heritage to the Remote Manipulator System (RMS) developed by the Canadian Space Agency (CSA) and used on the Space Shuttle and the International Space Station (ISS). In this case, the MARE arms are un-tethered, with interface fixtures on both ends; they would include minimal on-board power, and would instead draw power from the HexBus modules through which the arms connect with the platform; see below. As above, additional R&D studies and demonstrations are needed.

Propulsion / Attitude Control (PAC) Module Description

The Proulsion and Attitude Control (PAC) modules provide the required propulsion for guidance, navigation, and control (GN&C) and station keeping for the platform. Figure 5-11 presents a conceptual illustration of this module.

Figure 5-11 Illustrations of the “Propulsion / Attitude Control” (PAC) Concept



The PAC modules comprise: an electric propulsion unit (expected to be a type called a “Hall Effect Thruster”); a thruster pointing system (a modified MARE); tankage; required thermal management; and avionics. The total mass of the PAC module system will be driven by tankage requirements, and depends upon the planned duration of time between refueling. In other words, if the platform concept of operations (CONOPS) calls for refueling once every five (5) years, the tank size and mass on the PAC modules will be significantly larger than if the specification is for refueling and/or replacement once every two (2) years.

There are a number of design choices that must be made for the PAC modules, which are really the most complex in the entirety of the SPS-ALPHA architecture; including choices of electric thrusters (with metrics such as performance, cost, lifetime); choice of propellants and refueling approach and timing; guidance, navigation and control (GN&C); platform integration; etc.

SPS-ALPHA System Assemblies

From the eight required modular elements described above, all needed SPS-ALPHA concept “System Assemblies” are to be constructed, and from these in turn the entire SPS-ALPHA platform. The principal “Assemblies” that comprise the SPS-ALPHA spacecraft architecture are:

- Primary Power/Transmitter Array (PPTA)
- Primary Array Assembly (PAA), from which the PPTA is assembled
- Solar Reflector Assembly (SRA)

- Primary Structure Assembly (PSA)
- Connecting Truss Structure Assembly (CTSA)
- Propulsion / Attitude Control Assembly (PACA)
- Modular HexBot Assembly (MHA)

Figure 5-3 presented a high level conceptual illustration of this concept. Figure 5-12 presents another view of the same idea, including visualizations of both the individual modules and the Assemblies that would be constructed from them. Table 5-2 presents a matrix that summarizes the crosswalk between the eight (8) modular elements and the six (6) primary assemblies that comprise SPS-ALPHA. Details regarding the six assemblies are presented in the paragraphs that follow.

Figure 5-12 SPS-ALPHA Modules-to-Assemblies Illustration

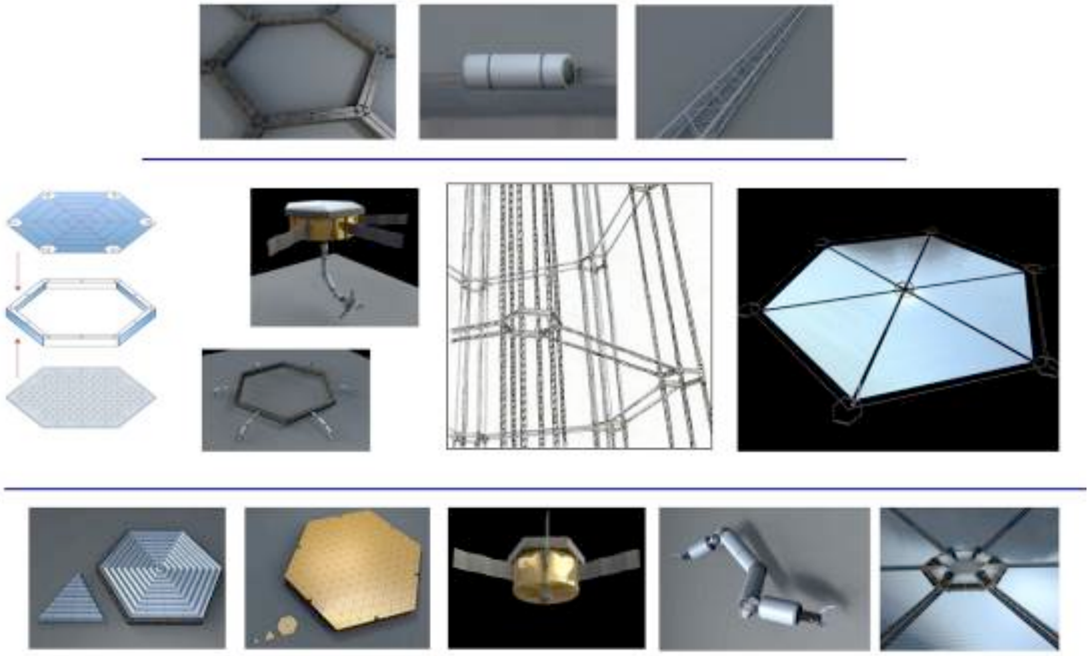


Table 5-2 Crosswalk from Modular Elements to Key Assemblies

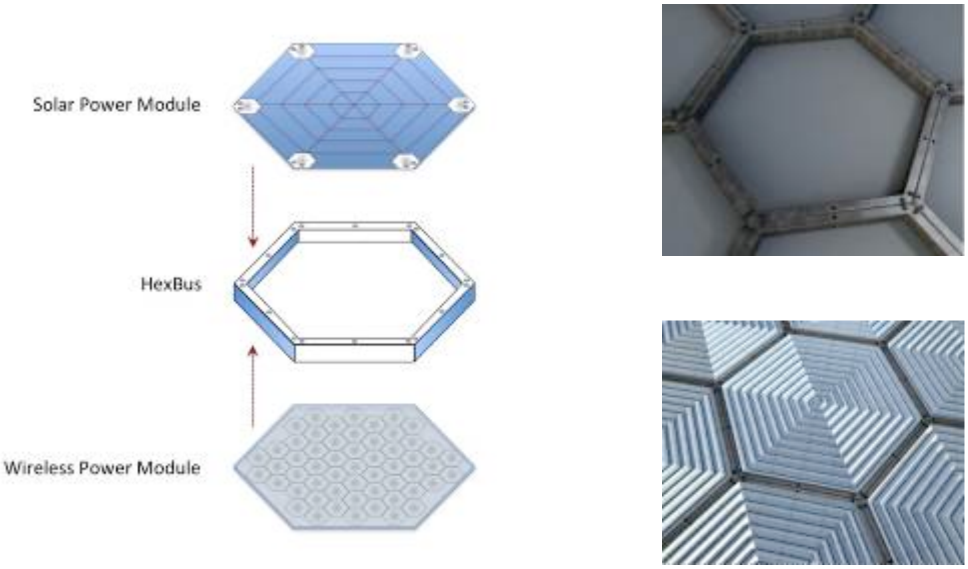
Modular Elements	**Key Assemblies***					
	Primary Array Assembly	Solar Reflector Assembly	Primary Structure Assembly	Connecting Truss Assembly	Propulsion & Attitude Control Assembly	Modular HexBot Assembly
HexBus	**X**	**X**	**X**	**X**	**X**	**X**
Interconnect	**X**	**X**	**X****	**X**	**X**	
HexFrame		**X**	**X**	**X**		
RDM Module		**X**				
SPG Module	**X**				**X**	
WPT Module	**X**					
PAC Module					**X**	
MARE Arms		**X****			**X****	**X**

*** As noted, the Power/Transmitter Array comprises multiple copies of the Primary Array Assembly, and is not listed separately*

** This Module / Assembly combination may / will require tailoring of the Module involved*

Primary Array Assembly (PAA). The Primary Power/Transmitter Array (PPTA) of the SPS-ALPHA (i.e., the disk at the base of the illustration in Figure 3-3) comprises many thousands of Primary Array Assembly (PAA) units. The PAA is assembled from four of the modular elements: the HexBus, Interconnects, an SPG Module, and a WPT Module. The PAA comprises the greatest number of modules as well as the majority of the mass (and cost) of the SPS-ALPHA concept. A conceptual illustration of the PAA is shown in Figure 5-13.

Figure 5-13 Illustrations of the SPS-ALPHA Primary Array Assembly (PAA)

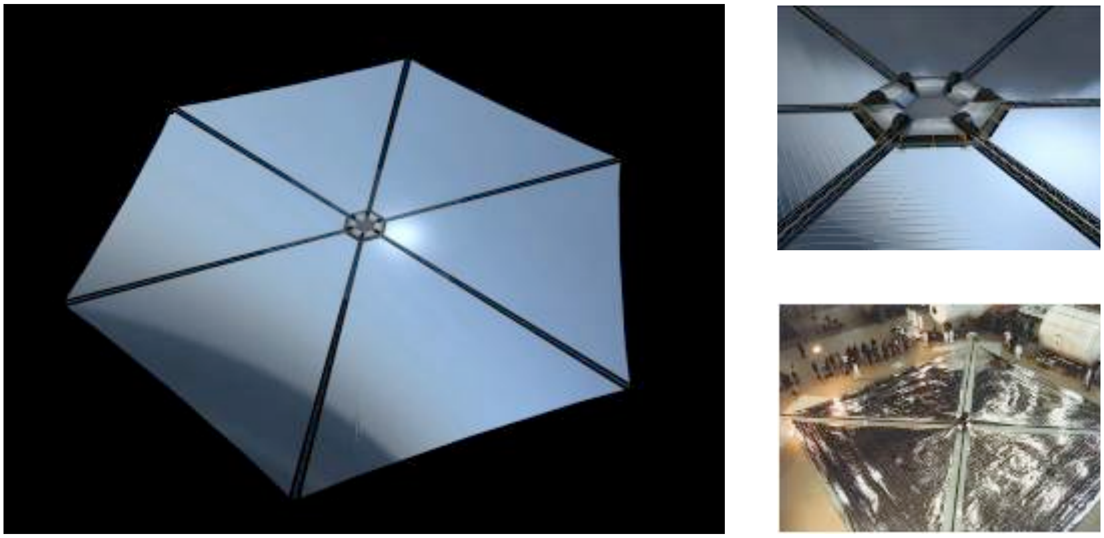


The image to the left is a diagram of the “stack” formed by a single HexBus, an SPG module, and a WPT Module; Interconnects are not shown. The image in the upper right is an illustration of how the HexBuses in the PAA would be linked by the Interconnects, and the image in the lower right is an illustration of how a number of assembled PAAs would appear on the back side of the PPTA, facing the Solar Reflector Assembly (SRA) described in the following section).

There are several architectural options for the PAA. The most important of these is the classic “Sandwich Module” approach in which all of the subsystems of the PAA shown in Figure 5-12 are fabricated as a single unit rather than involving three functional modules. (The integrated Sandwich Module approach may be used in a distinct SPS architecture, as discussed in Chapter 4, or could be incorporated in SPS-ALPHA.)

Solar Reflector Assembly (SRA). The SRA is assembled from five of the modular elements: HexBuses, Interconnects, HexFrames, RDM modules, and MARE Arms. A conceptual illustration of the SRA is shown in Figure 5-14. Note that the HexFrame structures shown around the edge of the reflector in the figure are part of the PSA, not part of the SRA. Figure 5-18 illustrates how several hundreds of SRAs are joined together in the PSA.

Figure 5-14 Illustrations of the SPS-ALPHA Solar Reflector Array

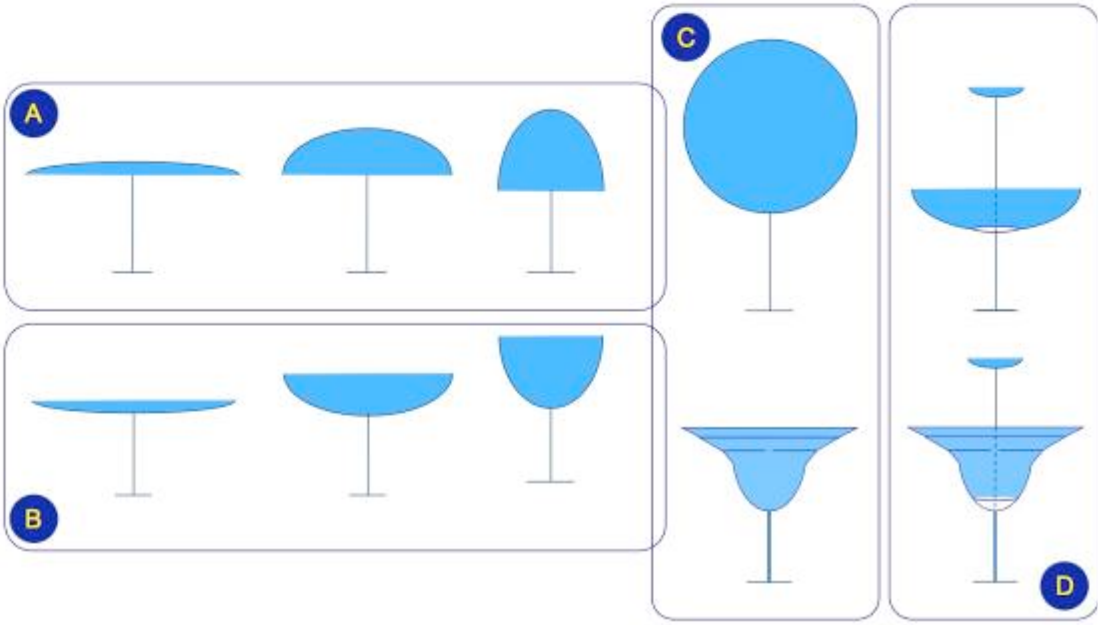


Note: SPS ALPHA Illustrations are on the left and in the upper right panel; the lower right panel presents a photograph solar sail test article (Credit DLR).

Detailed analysis is required to determine whether the assumption that a modified MARE Arm can provide the required pointing for the SRA's (in their role as Heliostats) is valid; if this is not the case, then a dedicated pointing system will be needed and must be added to the list of fundamental modules for the SPS-ALPHA.

Primary Structure Assembly (PSA). The Primary Structure Assembly (PSA) is the unmoving scaffold on which the individually pointed SRA heliostats are mounted. The PSA is assembled from three of the modular elements: the HexBus, Interconnects, and HexFrame Modules. There are a variety of different approaches that might be used to implement the PSA, with selection of the "best" option depending upon both the scale of the platform and the mission to be accomplished. An illustration of some of the wide variety of PAA configurations is shown in Figure 5-15.

Figure 5-15 Some High-level SPS-ALPHA and the Primary Structure Assembly Options



The primary alternatives appear to include the following options:

- **A** Options: A half-ellipsoid shape facing toward the PAA
  - Option A.1: a very shallow half-ellipsoid shape facing toward the PAA
  - Option A.2: a shallow half-ellipsoid shape facing toward the PAA
  - Option A.3: a deep half-ellipsoid shape facing toward the PAA
- **B** Options: A half-ellipsoid shape facing away from the PAA
  - Option B.1: a very shallow half-ellipsoid shape facing away from the PAA
  - Option B.2: a shallow half-ellipsoid shape facing away from the PAA
  - Option B.3: a deep half-ellipsoid shape facing away from the PAA
- **C** Options: More complex A structural shapes facing toward the PAA
  - Option C.1: a spherical frame
  - Option C.1: a sigmoid curve-based shape facing away from the PAA
- **D** Options: more complex hybrid optics facing away from the PAA

    - Option D.1: a simple curved figure curve-based shape facing away from the PAA with a secondary PPT structure positioned above the primary PAA (forming a Cassegrain-type optical configuration)
    - Option D.2: a sigmoid curve-based shape facing away from the PAA, with a secondary PSA structure positioned above the primary PAA (forming a pseudo-Cassegrain-type optical configuration)

Optimization of the specific PSA configurations will also depend on the details of the mission application or market to be served, including the total power to be delivered as a function of the time of day at any given receiving site. The sizing of the thin-film reflectors used to form the heliostats (minimum, maximum, etc.) will also influence system optimization. Figure 5-2 above presents computer renderings of SPS-ALPHA PSA configuration Options A.3, C.2 and D.2.[11]

On the next page, Figure 5-16 presents an illustration of an SRA installed within a single hexagonal "cell" of the overall SPS-ALPHA PSA. Figure 5-17 presents in turn a view of the several components of the PSA – beginning on the left with renderings of a single HexBus and a single HexFrame structure, in the middle with an sketch of a portion of the PSA (at a scale such that the HexBus modules at the corners of each cell are "dots," and finally on the far right with a close-up view of the PSA with SRA installed (and lying in the plane of the structure.)

Connecting Truss Assembly. The CTA is assembled from three of the modular elements: the HexBus, Interconnects, and HexFrames. A conceptual illustration of the CTA is shown in Figure 5-19. In the upper left images, a single HexBus module and a single HexFrame Structural Module are shown; in the lower left, a rendering of the overall CTA as seen from a distance is presented.

Figure 5-16 An SRA Integrated into a single Hexagonal "Cell" of the PSA

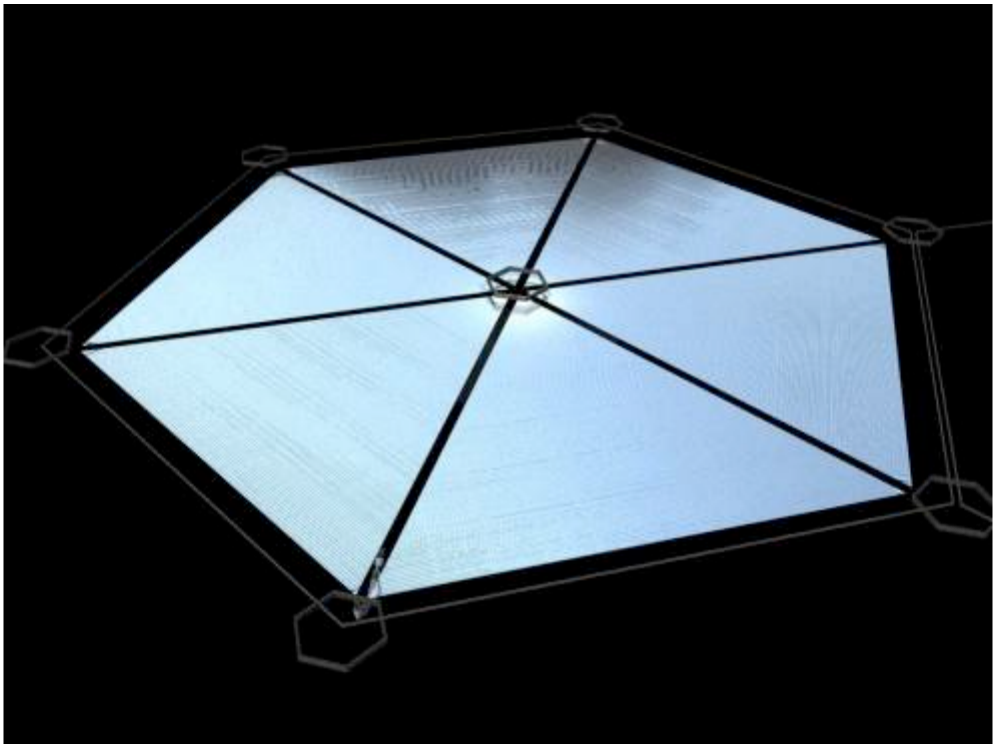


Figure 5-18 Composition / Sequence of the Primary Structure Assembly

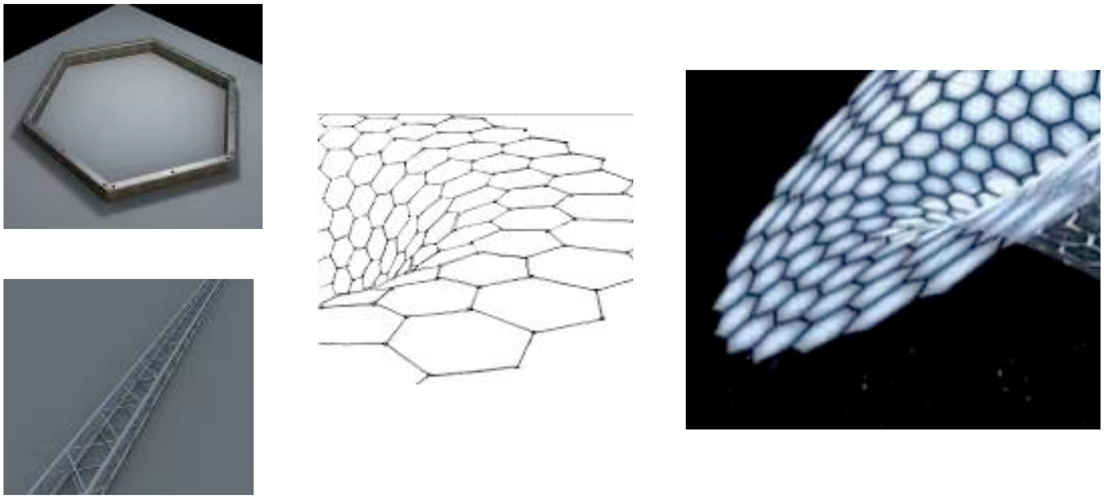
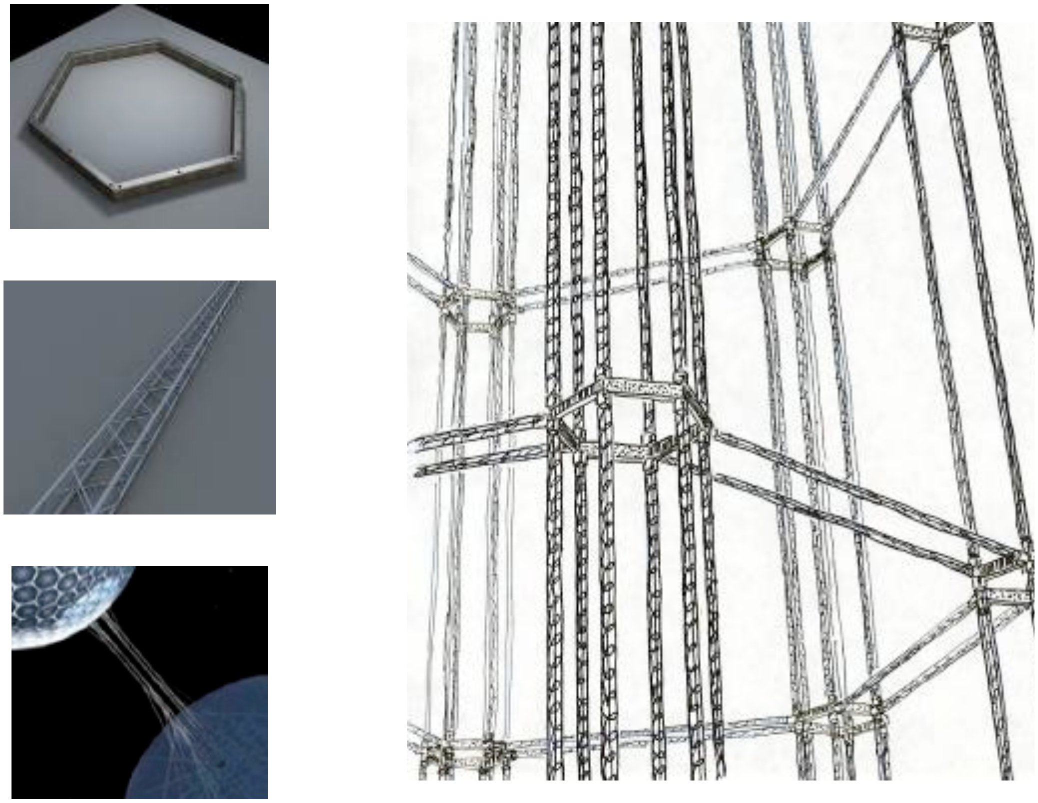


Figure 5-19 Illustrations of an Option for the Connecting Truss Assembly

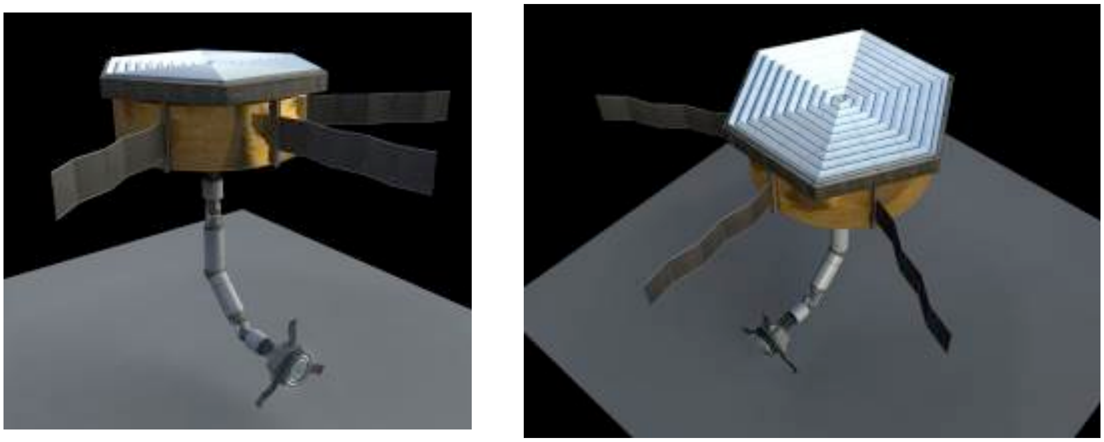


Propulsion / Attitude Control Assembly (PACA)

The PACA is assembled from five of the modular elements that comprise SPS-ALPHA: a HexBus, Interconnects, SPG Modules, a modified MARE system, and a PAC Module. A conceptual illustration of the PACA is shown in Figure 5-20. As shown, all parts of the PACA would be designed as ORUs (orbital replacement units). As a baseline, the tankage system, along with thruster and MARE interface, would be replaced when the propellant in a given tank was exhausted. However, refueling in place would be an option for further study.

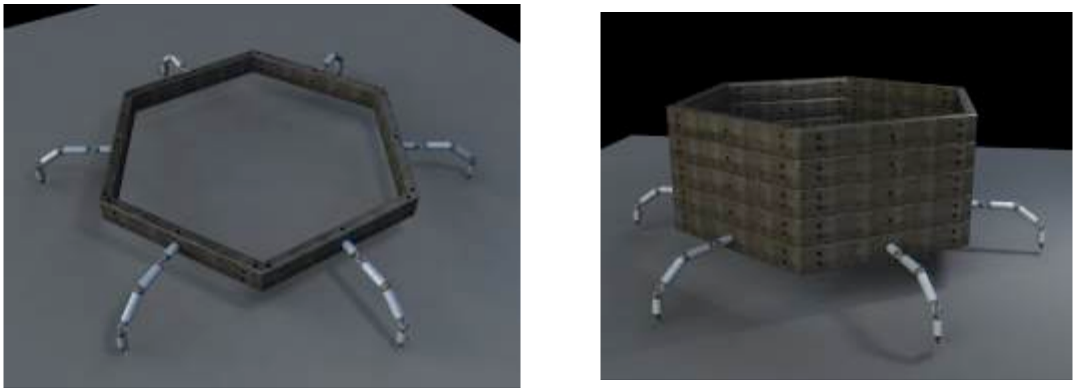
A rough estimate suggests that approximately 200 PACA's would be required for the full-sized, commercially competitive SPS-ALPHA for terrestrial markets. These units would be attached around the edges of the Primary Array, the Solar Reflector Assembly, and potentially at key locations (such as the base of the SRA at the CTA). This preliminary sizing and placement requires additional study.

Figure 5-20 Illustrations of the Propulsion / Attitude Control Assembly (PACA)



Modular HexBot Assembly (MHA). The basic MHA is assembled from two of the SPS-ALPHA modular elements: a HexBus, and a MARE robotic arm. Conceptual illustrations of the MHA are shown in Figure 5-21. The image on the left illustrates an MHA comprising one Hexbus Module and six integrated MARE arms. The image on the right is of an MHA carrying a stack of Hexbuses.

Figure 5-21 Illustrations of the Modular HexBot Assembly (MHA) Concept



Operating in this mode, each MARE arm would cooperate under the direction of the HexBus; all of the MARE's interacting and cooperating are through the use of the wireless router within the HexBus (noted previously).

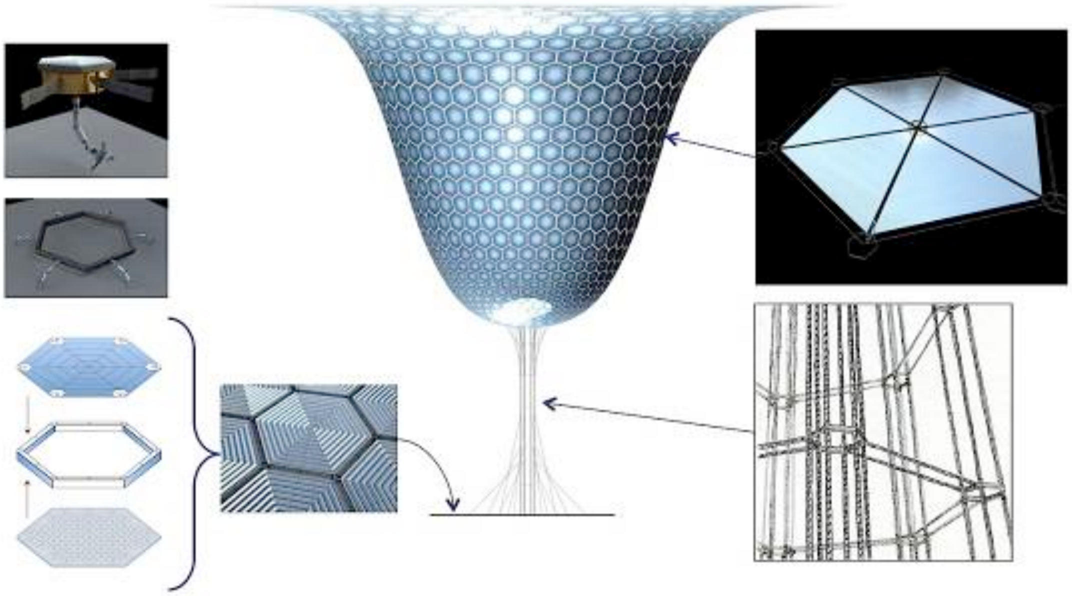
There is significant heritage for this type of robotic system through various R&D projects and prototypes including those developed at NASA's Jet Propulsion Laboratory (up to and including the "ATHLETE" wheeled rover that has participated in various human exploration concept of operations testing (under the auspices of the program known as "Desert Rats").

And that's it for our discussion of the eight different modules that are currently projected to comprise SPS-ALPHA and the intermediate level "Assemblies" that they will form. As promised, it is now time to consider how the modules and Assemblies combine to become the SPS platform.

Assembly to Platform Integration

As just described, the individual modules combine to form Assemblies; in turn, the six Assemblies are integrated to become the platform and its supporting systems. Figure 5-22 illustrates how the several Assemblies integrate to form the overall SPS-ALPHA platform.

Figure 5-22 SPS-ALPHA Assemblies-to-Platform Illustration



Secondary SPS Platform Systems. In addition to the primary end-to-end energy systems of the architecture, there are also a number of key technologies / functions that constitute the secondary in-space systems of the SPS-ALPHA platform; these include:

- Platform Structural Systems
- Guidance, Navigation, and Control (GN&C) / Attitude Control Systems (ACS)
- Platform Propulsion Systems
- Command & Data Systems (CDS)
- SPS Communications Systems
    - Including On-Board Communications, Space-to-Space Communications, and Space-to-Ground Communications
- Space Assembly, Maintenance and Servicing Systems (SAMS) – Platform based

Each of these will be integrated into one or more of the modules and Assemblies described above.

Ground Systems and Supporting Infrastructure

Finally, there are a number of key ground-based systems and supporting infrastructures that are required to accomplish the SPS-ALPHA architecture; these are summarized below.

Ground Systems. The following are the major elements that comprise the primary ground systems supporting a typical SPS platform.

- WPT System – Ground Receiver
    - Ancillary WPT Ground functions include WPT Beam Safety Systems
- WPT Ground Energy Distribution Interfaces
    - Power Grid Interface Option: Power Grid Interface(s), and Synthetic Fuel Production Interface(s)
- SPS Mission Operations Ground Infrastructure

Supporting Systems / Infrastructure. The following are the most important systems that comprise the common supporting infrastructure for a generic SPS platform.

- Earth-to-Orbit (ETO) Transportation
    - Functional capabilities include: ETO Launch Vehicles, Launch Infrastructure, and Mission Operations Ground Infrastructure.
- Affordable In-Space Transportation (AIST)
    - Functional capabilities include: AIST Vehicles, AIST Ground Support Infrastructure, and Mission Operations Infrastructure.
    - Option: For Reusable AIST, this may also include In-Space Supporting Infrastructure, with functional capabilities such as AIST In-Space Refueling Platform(s) and AIST SAMS Systems(s)
- In-Space Infrastructure
    - Including functional capabilities such as an SPS In-Space Refueling Systems(s) and SPS SAMS Systems(s).

Closing Observations

As a renowned Chinese military strategist and philosopher observed centuries ago, “the best victory is when the opponent surrenders of its own accord before there are any actual hostilities… It is best to win without fighting.” Many of the different concepts of Space Solar Power described in Chapter 4 attempted to solve one or more of the systems-level or technology challenges that faced the SPS 1979 Reference System by changing the baseline architecture. Each attempted to "win without fighting" in terms of a specific technical challenge. For example, to win the technical battle to achieve low mass, high voltage power management and distribution; to assemble a huge platform without factories in space; to achieve low cost from the first unit; and so on. SPS-ALPHA (and related hyper-modular concepts) follows on this course: it attempts to force the opponent's surrender – to win without fighting – by approaching the problem of Space Solar Power from a new direction.

Of course, there are a number of detailed technical areas that require additional study in order to refine and better characterize the details of the SPS-ALPHA concept. These include:

- Formal and detailed ray-tracing analyses are needed to allow better understanding of the solar flux delivered to the SPG modules on the Primary Array as a function of the location of the satellite in its orbit and the relative position of the sun at these points.
- Structural modeling (e.g., finite element modeling) is needed to determine CSI (controls-structures interactions) behavior and requires for the SPS-ALPHA for each of the several DRMs (defined in Section 5).
- Simulation of robotic assembly sequences and maintenance operations are needed – along with prototyping of systems – to finalize the design of the MARE and MHA concepts.
- A more detailed concept of operations (CONOPS), spanning launch, assembly, operations, and maintenance is needed for each DRM, including detailed scenarios and requirements for each module and assembly.

Despite the R&D yet to be accomplished, at present there are no apparent "show-stoppers" that might prove insurmountable to the basic technical feasibility of the SPS-ALPHA concept.

There are, however, a number of critical challenges to economically viable Space Solar Power that must still be addressed – some of them overcome by the SPS-ALPHA architecture, and others that must still be resolved. In Part III, which follows, we turn our attention to these hurdles.

[5-1] At the end of the 19th century, the Russian visionary Konstantin Tsiolkovsky (1857-1935) first conceived of the space age – multistage rockets, orbital stations, and the use of solar energy in space. Also, Isaac Asimov (who was mentioned in Chapter 2) described the idea of sending energy from space to Earth in a science fiction story in the late 1950s.

[5-2] In the sense that I am using the term, a "monolithic system" may still involve two or more identical piece parts. For example, the US Space Shuttle had three identical SSMEs (Space Shuttle Main Engines) and two identical SRBs (Solid Rocket Boosters); however, its basic architecture was certainly monolithic / integrated.

[5-3] A preliminary assessment of the technology needed for SPS-ALPHA is presented in Chapter 10.

[5-4] For example, see:

http://en.wikipedia.org/wiki/Concentrated_solar_power

http://en.wikipedia.org/wiki/Solar_power_tower

http://en.wikipedia.org/wiki/Solar_power_tower.

[5-5] For more information on IKAROS, see: http://www.jspec.jaxa.jp/e/activity/ikaros.html.

[5-6] See http://www-robotics.jpl.nasa.gov/systems/system.cfm?System=11 for information on ATHLETE (All-Terrain Hex-Limbed Extra-Terrestrial Explorer); http://ssl.mit.edu/spheres/ for information on SPHERES (Synchronized Position Hold Engage and Reorient Experimental Satellites), and http://blogs.smithsonianmag.com/design/2013/02/the-drones-of-the-future-may-build-skyscrapers/#ixzz2Qmcmtalb for information on the Flight Assembled Architecture Centre (FRAC) in Orléans, France.

[5-7] The masses presented in Table 5-1 are rough estimates only; detailed masses would vary depending on the specifics of each concept option. Also, the mass for the Propulsion and Attitude Control (PAC) module includes the mass of required propellants.

[5-8] This count may change over time; eight modules or seven, or nine – the architecture is unchanged.

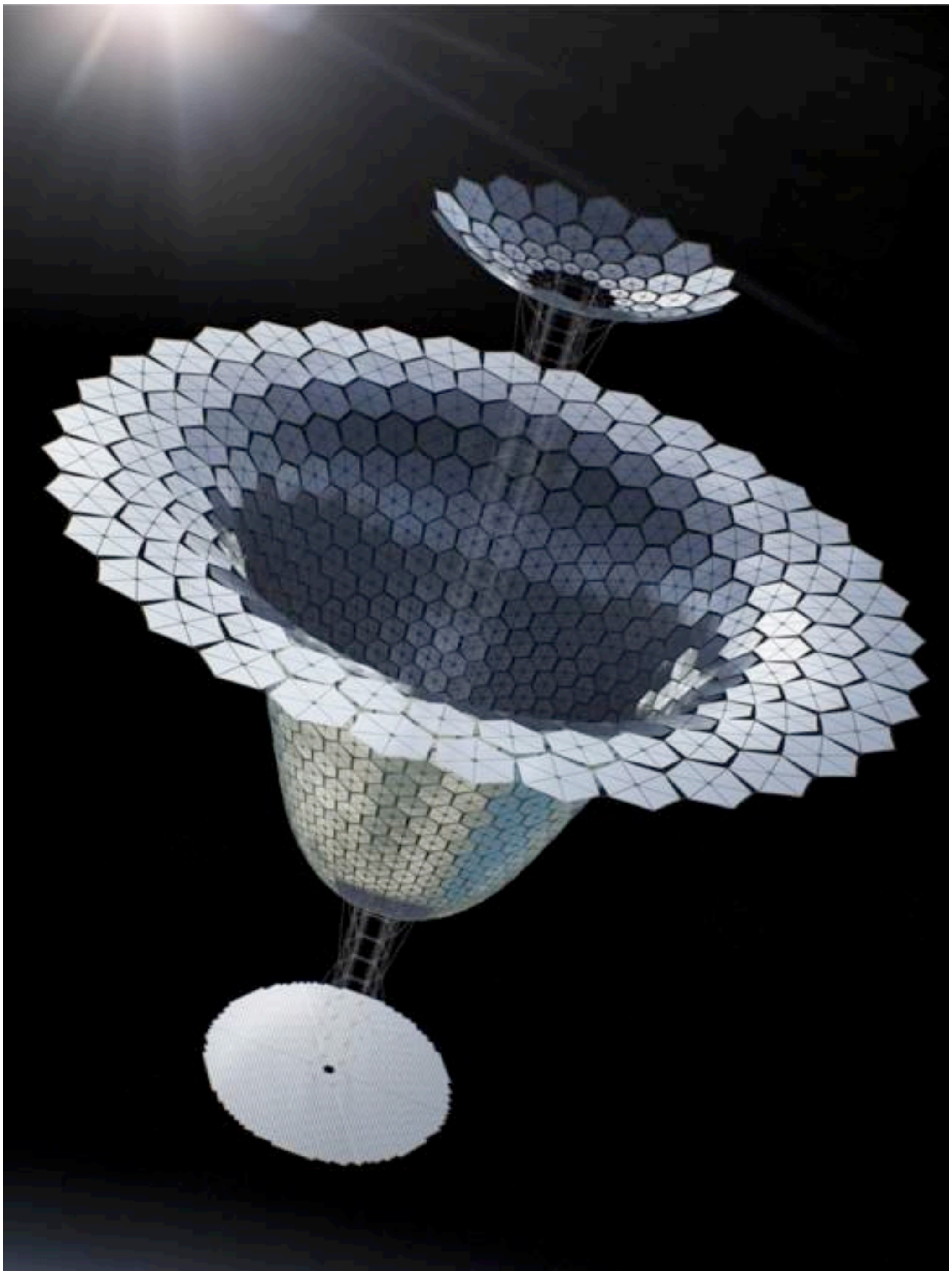
[5-9] External features, such a body-mounted solar array, etc.

[5-10] The specific antenna concept illustrated in Figure 5-9 is only one option; there are a number of alternatives, most of which are rectangular in configuration as shown in the photograph in the lower right-hand corner of the figure.

[5-11] The computer renderings above, as well as the numerous renderings of individual system modules, etc., in Section 3 of this report were done for this project by Mark Elwood of SpaceWorks Engineering, Inc.

Part III

Critical Challenges



Chapter 6
Affordable Space Hardware

That the automobile has practically reached the limit of its development is suggested by the fact that during the past year no improvements of a radical nature have been introduced."
Scientific American
(January 2, 1909)

Overview

In order of importance, the three most important economic hurdles that stand in the way of realizing large Space Solar Power systems are these: the cost of system hardware; the cost of transporting that hardware from Earth to its operational orbit; and the cost of operations and maintenance (O&M). There are, of course, additional challenges (such as achieving efficient and cost-effective wireless power transmission, the efficiency of solar energy conversion, etc.), and we've talked about some of these at the beginning Chapter 4. However, these are largely dependent on platform technology choices and performance. The factors discussed in this and the following two Chapters all concern dramatically lowering the costs of accomplishing ambitious future space missions. Of these, the high cost of space hardware is the single greatest barrier to affordable space missions.[1] And, in fact, the cost of hardware for use in space is typically much, much higher than the cost of anything we use in our daily lives.

This Chapter considers the problem of high space hardware costs for Space Solar Power, and challenges the notion that they must be high. It talks through the question of how these costs can be drastically reduced to enable future SSP systems.

What is the Problem?

Why are the costs of space hardware so high? Is it because doing things in space is inherently expensive? In my view, there are several reasons.

First and foremost, space systems have usually been developed specifically for a particular mission or set of missions, and only a relatively small number of copies (often, only a single copy) have been fabricated and deployed. Table 6-1 illustrates this point with several examples.[2]

Table 6-1 Examples of Systems Prices / Costs and Numbers of Copies[3,4]

Example System		Number of Copies	Unit Price ($)	Mass (kg)	Specific Cost ($ / kg)
"Ground" Systems	Automobile (Sedan)	300,000	~ $40,000	~1,800 kg	$22/kg
	Personal Computer (Laptop)	>100 M	~ $500	~2.5 kg	$200/kg
	Smart-Phone	> 50 M	~ $200	~0.11 kg	~$1,800/kg
	Commercial Airliner (Boeing 747 Class)	> 1,100	~$250 M	180,000 kg	$1,400/kg
Space Systems	ELV (Delta IV Heavy Class[5])	~ 30[6]	~ $270 M	~90,000 kg	$3,000/kg
	US Space Shuttle Orbiter	~ 5	~ $4.5 B	~80,000 kg	$86,000/kg
	Navigation Satellite (GPS Block II/IIA Class)	> 28	~ $50 M	1,000 kg	~$33,000/kg
	International Space Station	1	~ $50 B	~450,000 kg	~$110,000/kg
	Mars Rover (Spirit/Opportunity Class)	~ 2	~ $200 M	~200 kg	$1,000,000/kg

As shown in the table above, hardware costs are usually discussed in terms of the “cost per unit mass” – in other words, “dollars per kilogram” or “dollars per pound.”[7] It should be noted that in many of these examples – e.g., automobiles, laptops, smart-phones, etc. – there is strong heritage from one product generation to the next. As a result, the start-up cost of related manufacturing efforts can be substantially less than for a first time production start-up.

Secondly, and driven by the first factor (space program development), fabrication and testing tools and methods are not typically chosen with an eye toward mass production; rather, they involve a great deal of highly-skilled “touch labor” performed in expensive-to-maintain “clean rooms” (i.e., rooms from which potential contaminants such as dust have been carefully removed). Moreover, locations in space are remote; reaching orbit, the Moon, or beyond is expensive and time-consuming for machines, and more so for astronauts. As a result, space systems incorporate high levels of fault tolerance, such as redundant subsystems.[8]

Also, the environment of space is very harsh compared to most locations on Earth, including exposure to vacuum, radiation, intense sunlight and bitter cold, and more. All of these factors drive up component and systems costs, particularly in cases where a specific device – perhaps a memory chip or a processor – must be “Rad-hard” (i.e., radiation hardened, meaning that the device must be capable of operating with little or no risk of failure in the radiation environment of space). Even before the system gets into space, it must first endure the rigors of launch, such as severe shaking due to the tremendous vibrations that can occur and extremely loud acoustic environments.

In addition, space systems are almost always launched as single, monolithic packages atop a single, very expensive, general-purpose expendable launch vehicle in which special interface equipment may have been installed. Because launch is expensive and opportunities to launch are rare, system designers try to fit every possible bit of capability into a tightly constrained payload capacity. Spacecraft designs have often been altered to skim smaller and smaller amounts of mass out of the system, leading to special manufacturing and testing requirements – and to increased costs.

Space hardware costs can also be influenced by various management-related factors, including contracting practices, the presence (or lack) of competition, poor or just inexperienced management, and so on. Purchasing hardware by means of “cost-plus-fixed-fee” (CPFF) contracts removes incentives for vendors to lower their costs of manufacture – after all, if a firm reduces the cost it also reduces the fee that it might receive. Fixed price contracts can be far more effective at lowering costs – while making them more predictable – but only if the customer (typically the government) is willing to allow the vendor to make a greater profit. If there is a single vendor, the absence of competition may mean there is no motivation to drive down costs. However, even if there are two or more vendors, CFFF practices can still remove any motivation to lower costs. “Rose-colored glasses” worn (metaphorically) by an inexperienced manager or overly optimistic bid and proposal (B&P) team leader can result in what are called “low-ball” estimates that later balloon when they encounter the cold light of reality during project implementation.[9]

The standard tool in space system cost estimation in the US is known as “NAFCOM” (the NASA-Air Force Cost Model), developed years ago and still maintained. The model incorporates diverse, statistically-defined cost estimation relationships (CERs) that are based fundamentally on hardware mass but adjusted for various other design and programmatic considerations (such as complexity, system maturity, and so on). NAFCOM does not incorporate many – if any – historical data that involve large numbers of small modular elements, as does the SPS-ALPHA concept.

Another but sometimes overlooked management-related factor in cost overruns and schedule delays is the decision to proceed with the development of a new system using immature technology. In almost all space systems projects, there is a key decision point in the project life cycle known as the Critical Design Review (CDR), at which time designs are to be “frozen” (i.e., not changed any further), technologies are to have been proven and vendors identified, and cost estimates – assumed to be accurate – completed. But in all too many cases, the technology to be used is not really mature, and if this is the case, then how can any design truly be finalized or costs really known? For the past decade and more, the US General Accountability Office (GAO) has been hammering on this topic as a huge cost issue across multiple US government system development programs and agencies, under the *nom de guerre* “Knowledge-Based Acquisition.”[10]

So, how <u>can</u> the hardware costs of large space systems such as Solar Power Satellites be dramatically reduced? Is it even possible? Obviously, I believe the answer is "yes." We'll spend the next several pages exploring how this goal can be accomplished.

Getting Costs Down

There have been several attempts to get space hardware costs down during the past two decades and more; several of these attempts are sketched in the paragraphs that follow.[11] In addition, there are still other – perhaps more promising approaches – that have not yet been tried.

Faster, Better, Cheaper.[12] Perhaps the most famous of the past efforts to lower the cost of space missions was at NASA in the 1990s; it was called "faster, better, cheaper." This clever phrase played on the fact that in any project there are three basic and inter-independent characteristics that a good manager can adjust: (1) performance; (2) schedule; and (3) cost. The introduction of highly focused small satellites – a.k.a., "SmallSats" – in the early 1990s was an important part of this movement.

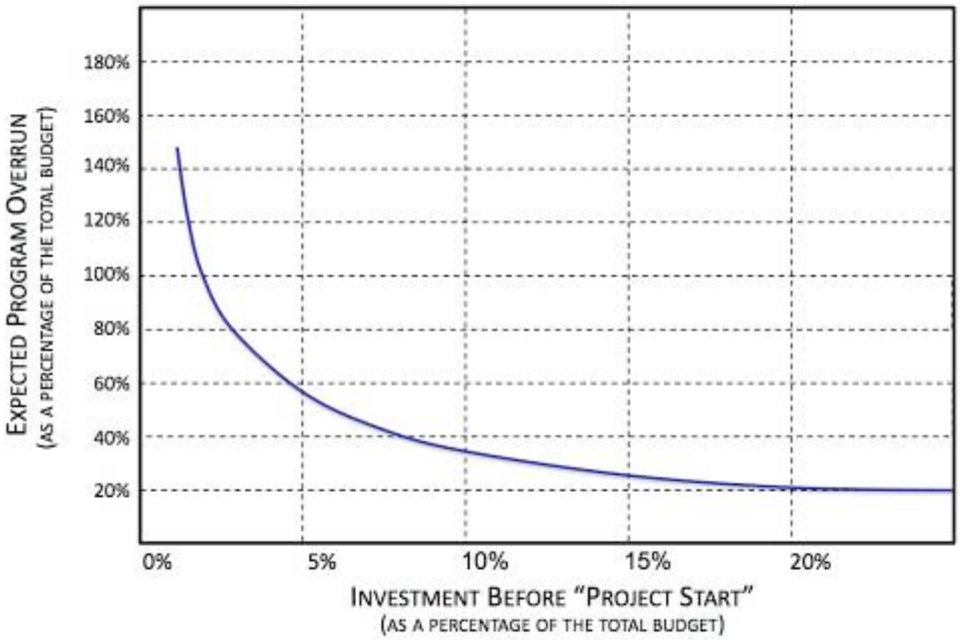
The central idea was a good one: smaller satellites <u>can</u> cost less than large ones. However, SmallSats typically achieve this cost savings by <u>doing</u> less: a small satellite might carry a single payload rather than a dozen; it might have less than 100 watts of solar power rather than several thousand; and so on. In many cases, these innovations closely resemble a return to the much smaller and cheaper spacecraft that were flown in the early days of the space age.

New Ways of Doing Business. At one point, another catch phrase at NASA for reducing the cost of space missions was "new ways of doing business." This concept was clearly right, while its implementation was clearly wrong. "New ways of doing business" may have the potential to lead to lower costs. However, to be effective in achieving this laudable goal, the concept must be followed by the introduction of new management practices (such as "lean" practices in software development) and by new systems architectures (such as the hyper-modular, networked approaches that characterize SPS-ALPHA). If the only "new" aspect of a development project is the assertion that systems engineering overhead (and oversight) will be minimized, any resultant savings may scarcely justify the increased project risk.

Design and Technology Maturation. Technology and system design maturity can also play a critical role in space program cost. A budget analyst at NASA Headquarters performed a wonderful analysis of this problem in the late 1980s.[13] As shown in Figure 6-1, while Werner

Gruhl was the chief of the Cost & Economic Analysis Branch in the Office of the NASA Comptroller at NASA Headquarters, he found that there was a strong correlation between the investment made in system design studies and technology maturation <u>before</u> freezing the design and budget estimate, and the probability of a cost overrun after that point.

Figure 6-1 Impact of Failing to Invest Before Project Start



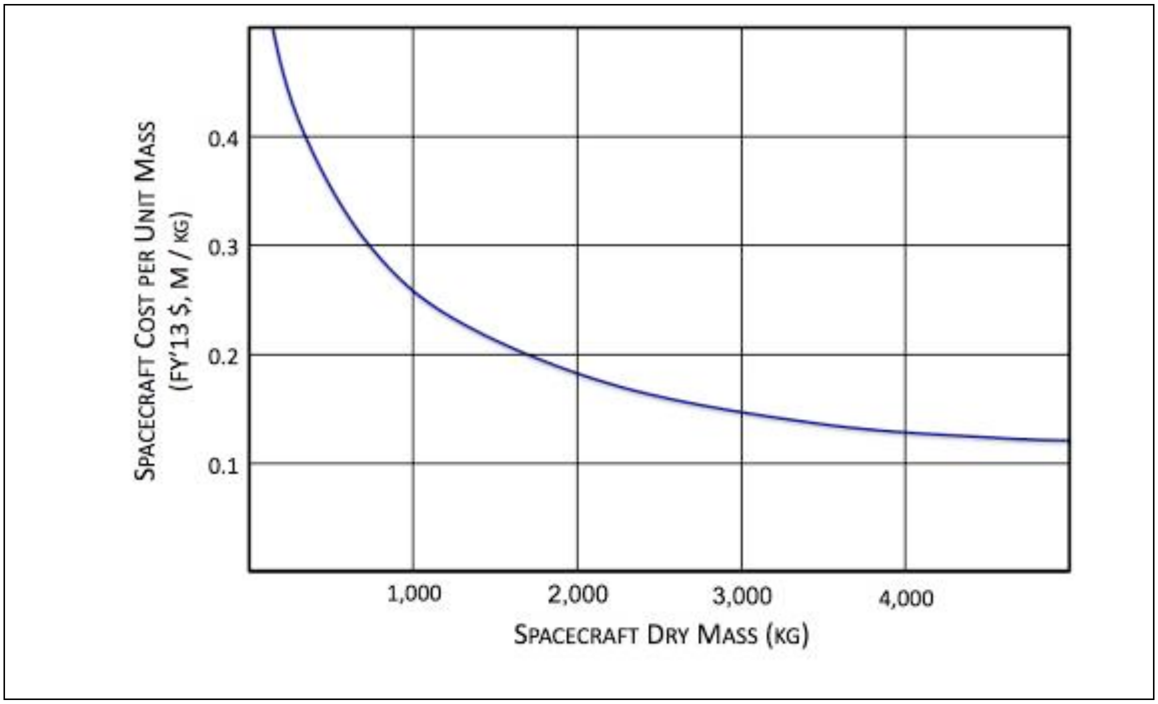
Credit: Artemis Innovation Management Solutions LLC (2013); Data Source: W. Gruhl / NASA Presentation; 1987.

What Gruhl's data demonstrated was that if more than about ten percent (10%) of the eventual total program cost was invested before the Critical Design Review, when cost estimates are typically fixed, then any later cost overruns were less than about twenty-five percent (25%). However, if the pre-development investment in design studies and technology R&D was less than about five percent (5%) of the eventual total cost, then cost overruns were never less than eighty percent (80%). This observation is at the heart of the GAO's campaign to promote the use of "Knowledge-Based Acquisition," mentioned previously. The standard practice then would have been to do the necessary homework (more than 10%), make the best possible cost estimate, and then add an additional 20% of "margin" to that estimate.

System Scale. Yet another design parameter related to the cost per unit mass of a space system is the total mass of the system being developed; in particular, the smaller the system the greater the cost per unit mass. Figure 6-2 illustrates this point.[14,15] This observation depends on several key assumptions. The types of systems must be similar to one another and the technology involved (e.g., materials) should be comparable, etc. (This is intuitively obvious: clearly a one-kilogram block of Aluminum will not cost as much per kilogram as a one-kilogram lap-top computer!)

Also, the mission goals and complexity must be comparable for this comparison to be meaningful. (Metaphorically speaking, you might be able to squeeze "ten pounds of science" into a "five pound sack," but it's going to cost you!). The smaller the spacecraft dry mass, the greater the cost per unit mass (i.e., dollars per kilogram) becomes. As sketched, development of a new 500 kg planetary spacecraft could cost approximately $200,000,000. Similarly, the cost to develop a 3,000 kg planetary spacecraft might cost on the order of $450,000,000. There is an upper limit, fortunately: even very small spacecraft (e.g., 10 kg or less) costs no more than roughly $1M-$10M per kilogram. What this implies is that, even though it is possible to reduce the cost of a space mission by reducing the mass of the system, the *cost per unit mass* will increase dramatically. Next: let's take a closer look at the importance of mass production.

Figure 6-2 Relationship of System Size to System Cost per Unit Mass



Credit: Artemis Innovation Management Solutions LLC (2013)

*The Experience Curve***.** The single most important concept for the low-cost manufacture of advanced technology systems is that of the so-called "experience curve." This notion is obvious to anyone who has ever manufactured anything: when one makes a large number of the same product, the 100th copy costs less to make than the very first copy; the 10,000th copy costs less than the 100th copy, and so on. Of course, this observation depends on a number of other factors, including the availability and cost of input components, the availability and cost of labor, and others.

Thomas Wright, an engineer with the Boeing Aircraft Company some four generations ago, first characterized mathematically the "learning" effect that reduces the cost per unit with increasing production. In the 1930s, he observed that with each unit produced of a particular airframe the required average number of direct labor hours dropped in a predicable fashion.[16] Wright described this effect as a "Progress Curve"[17] and discovered that this powerful concept could be expressed mathematically as a simple equation:

$$H_N = H_1 * (N)^f$$

where H_N = Recurring Labor Hours per Unit; H_1 = Labor Hours for the First Unit; N = the total Number of Units Manufactured; and f = a constant factor with a value less than zero ($f < 0$) that characterized the rate at which cost per unit drops as the total number of units produced increases. (In this case and others, the size of the "unit" is unchanging and therefore the effect becomes a reduction in the cost per kilogram with increasing production.)

This concept was later expanded and applied to a range of systems, first to weapons systems in the 1950s by the RAND Corporation, and then in the 1960s by the Boston Consulting Group (BCG) to a variety of industries.[18] There is considerable evidence that this effect is real, although there are several theoretical variations on the simple equation that Wright first published. Practically speaking, there are a number of details that must be considered, including answers to the following questions, to name just a few:

- How large is the "unit" system to be fabricated and how long does it take to produce a single unit?
- Before production starts, how many units are expected to be manufactured, and what investments are made in the means of production (for example, to what degree are the means of production automated)?
- What are the type, scale, and number of parts that comprise each "unit," and what are the answers to the first two questions above for those parts?
- What external factors drive mandatory fixed labor costs, independent of production (e.g., government quality and/or safety requirements)?
- What is the existing experience base for the technology and/or system, and to what extent can that knowledge be adopted directly by a "new" production effort?

"*The Goldilocks Rule*." Everyone may be familiar with the children's story of "Goldilocks and the Three Bears," and how the young house-breaker Goldilocks ended up rejecting options that were too hot or too cold, too hard or too soft, and so on, and instead consistently choose the option that was "just right." I would like to add to the discussion of modularity and mass-production the concept of the "Goldilocks Rule" for space systems scale. In particular, spacecraft that are too small may be incapable of performing many missions of significant value by themselves; however, large spacecraft may prove to be prohibitively expensive or even too large to launch with available ETO vehicles. Even in a modular architecture, space systems modules that are too small may require too much "overhead" in non-productive interfaces, while modules that are too large will not result in truly lowering the cost of space systems hardware by means of mass production.

I would like to characterize the result of balancing these competing considerations as "*The Goldilocks Rule*" for space systems – particularly those that are intended for use as modules in a larger system-of-systems to be assembled later. They should be large enough but not too large, small enough but no smaller; they should instead be "just right." They must be small enough for convenient (and automated) mass production, but not so small that they cannot perform the mission. Also, for modular systems, each module cannot be so small that interface costs (which are basically non-productive overhead) outweigh the benefits of smaller sized, mass produced modules.[19]

Space Systems Costs and Space Solar Power

Just how bad is all of this for SSP? As we saw above, in the case of a large conventional-architecture spacecraft, the cost per kilogram will typically be somewhat lower than that of a SmallSat using comparable technology, but not significantly lower. For example, if the cost per kilogram is \$20,000 per kg (a pretty good number for conventional space systems), and if the total platform mass is 10,000,000 kg for an SPS that would deliver 1 GW (i.e., 1,000,000 kilowatts) to Earth, then the total cost for this platform would be roughly \$200,000,000,000 – or about \$200 billion! And the contribution just from that initial hardware fabrication cost to the overall levelized cost of electricity (LCOE) for energy delivered from this SPS would be a bit less than \$1.00 per kilowatt-hour.[20] Once one adds in the additional costs of in-space infrastructure, space transportation, operations and maintenance, etc., the LCOE would be even farther from the goal of commercial viability.

The root causes of the historically high costs of space hardware include the following:

- The small numbers of copies of space systems that are manufactured, and the resulting lack of mass production tools (e.g., there are no assembly lines, etc.)
- Designing to endure the rigors of the space environment, and the need for special materials and components,
    - This includes especially the rigors of launch to space (vibration and acoustic);
- Higher levels of redundancy as a contingency against system failure.
- Special design and fabrication efforts to reduce system weight.
- Management factors, including

  - Acquisition approaches that can engender cost growth, such as CPFF;
  - Lack of competition in vendors and/or an unwillingness to cancel projects if they overrun estimated budgets; and,
  - Failure to achieve adequate design and technology maturity before the beginning of full-scale system development.

All of these factors have historically contributed to the exceptionally high costs of space systems hardware when compared to the prices we pay for all manner of very advanced technology systems in our daily lives. Fortunately, there appear to be no fundamental barriers to dramatically reducing the hardware-related costs of future space systems, including ambitious mission goals such as Space Solar Power.[21] Several steps must be taken to achieve this objective, including:

- Implementing modular design architectures;
- Designing modules to enable low-cost mass production;
- Designing modules to enable the use of affordable components;
- Maturing technology to be used, and system designs before freezing those designs and beginning production;
- Applying the "*Goldilocks Rule*" rigorously; and
- Developing and demonstrating production techniques and manufacturing systems along with SSP technologies and systems.

What does the above discussion suggest? Simply this: although standard tools, such as NAFCOM (described earlier) may be useful in estimating the costs of initial flight system development for a single SPS-ALPHA module, they will not be accurate in estimating the systems-of-systems level costs for 1,000 or 100,000 of those modules. Of course, accurate estimates will require prototyping of the several modules, and empirically determining the costs as the number of units manufactured increases. Nevertheless, some sort of preliminary estimates are essential both to inform SPS-ALPHA design decisions and to develop the best-possible estimates of the economic returns that space solar power might achieve. To attempt such a preliminary estimate, we must turn to modeling techniques that are far simpler – but not necessarily less accurate – than sophisticated tools such as NAFCOM.

SPS-ALPHA Costs

One of the principal objectives of the SPS-ALPHA NIAC Phase 1 project was to "conduct an initial evaluation of the economic viability of the concept (as a function of key performance parameters)." The project's economic analysis comprised several aspects (as illustrated above), including development of an integrated market model and identification of prospective space mission applications.

A crucial aspect of the evaluation of economic viability is appropriate and consistent estimation of the cost of the system under consideration. The heart of the SPS-ALPHA concept is the idea that a hyper-modular architecture will result in dramatic reductions in the cost per kilogram for platform systems through mass production. As described in Chapter 5, SPS-ALPHA de-constructs into a number of "Assemblies," which in turn are composed of a number of "Modules." This architecture is reflected in the cost estimation approach that has been used in the current study. As a result of the systems analysis effort, individual modules have been sized by mass, and cost estimates developed for each module.

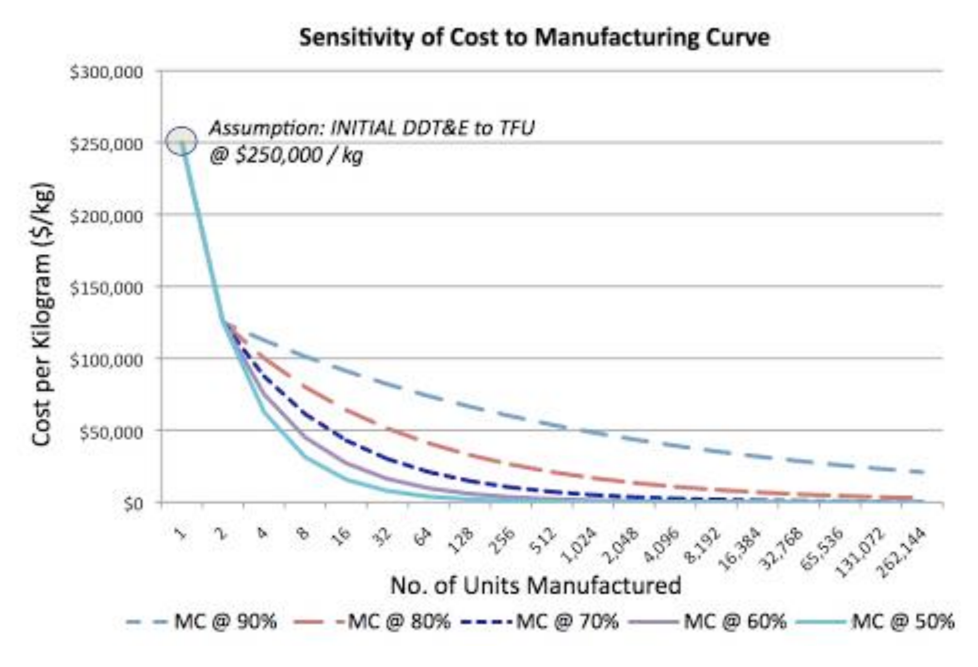
At the level of analysis possible, given the scope of the NIAC Phase 1 project and the level of maturity of the concept, cost estimates for each module were based on a simple mass-based cost estimation relationship (CER). The CER for each module is defined based on the type of module (referenced to historical spacecraft cost data) and adjusted down with increasing module production. This effect is typically characterized as a "learning curve" (LC) or "manufacturing curve" (MC) for the involved hardware. The LC/MC is based on the historical observation that, given a specific physical system, the number of units manufactured is related to the CER (i.e., cost per kilogram) of the units produced by three parameters: (1) the initial CER for the first unit developed and fabricated, (2) the expected cost of the second (identical to the first) unit produced, and (3) a projected percentage change in the CER for every doubling of the number of units produced. For example, if an initial unit has a CER of \$100,000 per kilogram, with a fabrication cost of the second identical unit of \$50,000 per kilogram, and the LC/MC is 50%, then the CER for the eighth (8th) unit manufactured will be \$12,500 per kilogram.

For the SPS-ALPHA NIAC Phase 1 study project completed in 2012, the initial CER was set for each module based on the type of module, and the reduction in cost for the second unit was assumed to be 50%. The LC/MC is set by assumption, with reference to relevant historical aerospace systems cases. Clearly, the cost estimation assumptions used are essential drivers of the results of any evaluation of economic performance. A key question is: how sensitive are those results to these assumptions?

Figure 6-3 illustrates the effects of the LC/MC for several different values, beginning with an initial CER of $250,000 per kilogram and a cost reduction for the second unit of 50%. Figure 6-4 provides a close-up view of a portion of Figure 6-3, focusing on the portion of the overall curves below a CER of 10,000 per kilogram. The chart highlights the approximate threshold for SPS-ALPHA economic feasibility at about $500/kg for system manufacturing cost. As shown, an LC/MC at 50% falls below the threshold at approximately 260 units manufactured; an LC/MC at 60% falls below the threshold at approximately 2000 units, etc.

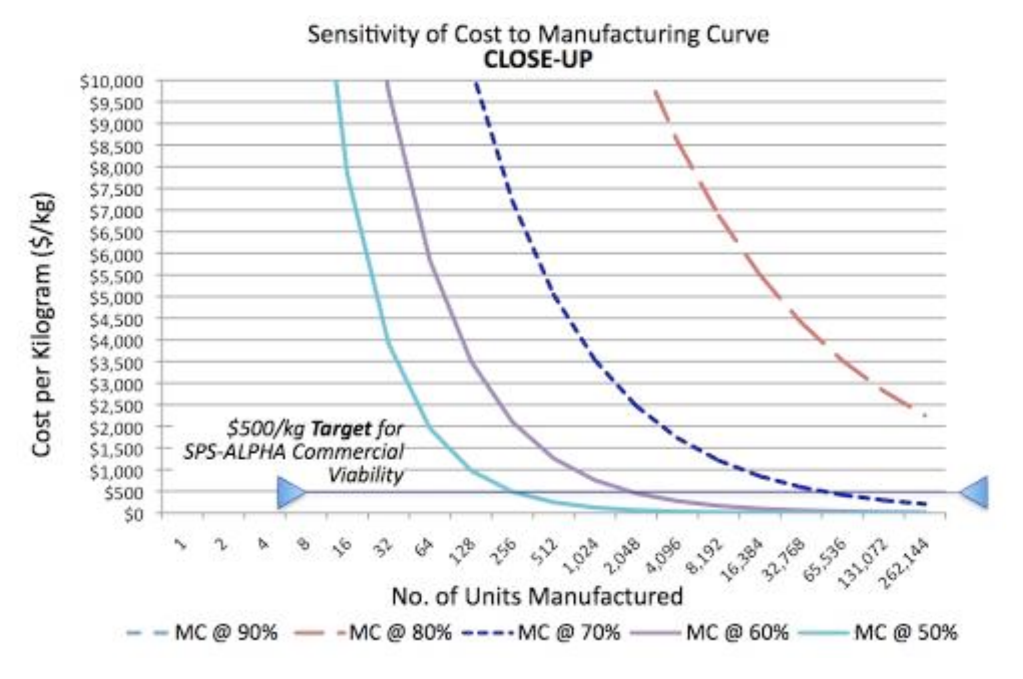
Since production runs for large, highly modular Solar Power Satellites would involve from many 1000s to millions of modules, extremely low costs should be realizable relatively quickly so long as the LC/MC is 70% or lower. Even with an LC/MC of 80%, very low costs may be achieved for production runs involving multiple SPS. The LC/MC used in the analysis (and the justification for this assumption) are described in Chapter 10.

Figure 6-3 Analytical Examples of the Learning/Manufacturing Curve



Credit: Artemis Innovation Management Solutions LLC (2012)

Figure 6-4 Close-Up View of a Portion of Figure 6-3



Credit: Artemis Innovation Management Solutions LLC (2012)

One More Thing… How Much Modularity?

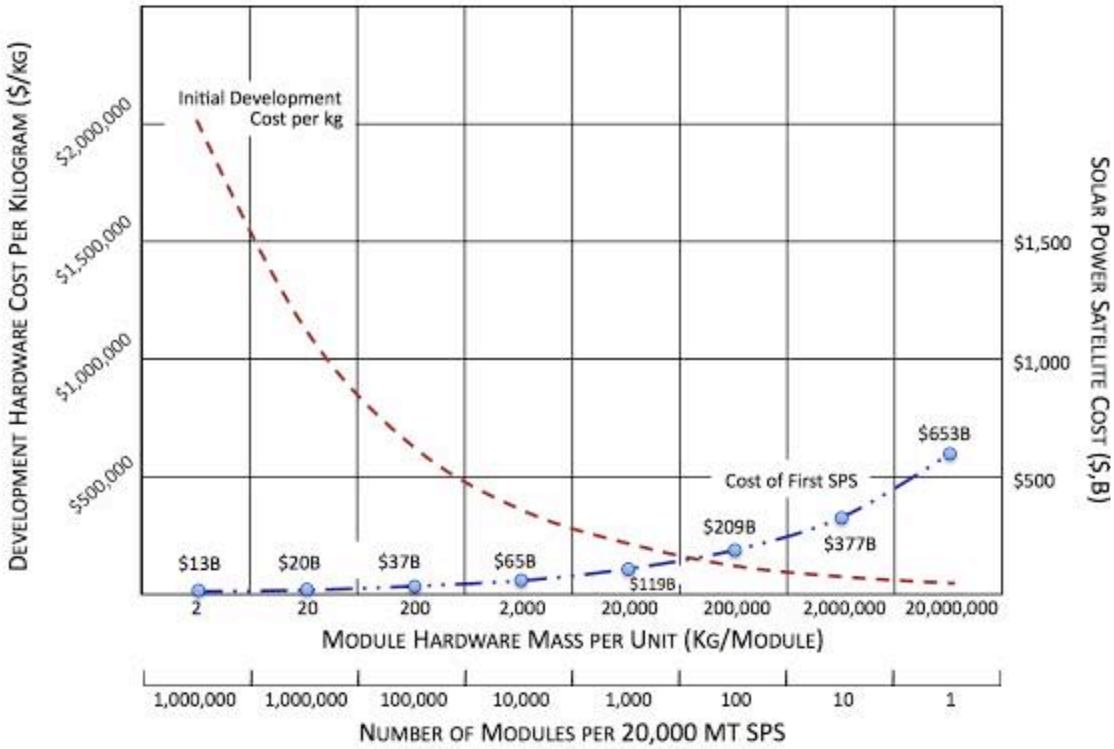
As noted above under the heading "the Goldilocks Rule," a good general question for SPS architecture definition is this: how much modularity is the right amount? As noted previously, larger space systems tend to cost less per kilogram to develop than similar smaller systems. Moreover, modular architectures inevitably involve some mass and cost penalty due to the need for integration of the modules. How great a penalty is too much? For many in the space sector, the existence of these issues (and some others) has been enough to preclude them from considering modular systems approaches, and to instead favor traditional, monolithic architectures.

Fortunately, the additional hardware needed for integration in a modular system concept is itself amenable to mass production at affordable costs. With a reasonable "learning curve" (i.e., one consistent with other aerospace systems), modular architectures for Solar Power Satellites can not only be competitive but in fact superior to integrated systems performing the same mission. In order to illustrate this point, I prepared a generic analysis of the problem, presented in Figure 6-5.

As shown, the figure plots (a) the initial hardware development cost per kilogram for an SPS "module" and (b) the total cost of an assembled SPS with a total mass of 20,000 MT, *as a function of* (c) the total number of modules comprising the Solar Power Satellite. Recall that historically – as illustrated in Figure 6-2 – the cost per kilogram for development of a system drops with the increasing size of the system; the largest system has the lowest initial *cost per kilogram*. However, for increasing numbers of modules, the learning curve comes into play, driving down the cost per system for platforms involving large numbers of modules; the most modular architecture will result in the lowest *cost per SPS*.

Figure 6-5 graphically illustrates the principal economic advantage of the SPS-ALPHA or other, similar, hyper-modular architectures: for a Solar Power Satellite composed of modules that have a mass greater than about 10 MT, the cost of just the fabrication of hardware for the first SPS platform exceeds $100B – and this value does not include the cost of launch, or of in-space transportation or infrastructure, or of operations & maintenance of the platform. As a result, the figure highlights one of the economic difficulties for the SPS concepts that emerged from the 1990s NASA studies (such as the SunTower): a moderate degree of modularity reduces costs meaningfully, but not nearly enough. Only hyper-modular architectures can make possible the exceptionally low hardware costs that we take for granted in our daily lives and make possible the potential for SPS economic viability.

Table 6-5 Relationship Between Number of Modules and Costs[22]



Two last points on this topic. First, there is a limit to dividing the system into more and more modules. At some point, the integration penalties become too great and, at a fundamental level, the cost per kilogram of the smallest module cannot be less than the cost of the materials and devices that make up that module. Also, if one looks more strategically at the fabrication and deployment of a large number of Solar Power Satellites – for example, 100 or more platforms – then the cost contribution of the SPS hardware to the cost of electricity will drop still further. In other words, if one plans to deploy 100 SPS or more, a module size of 2,000 kg could become competitive; however, for the first SPS it will cost much more than a platform comprised of 20 kg modules. This macro-scale learning curve effect was central to the economic argument for the US Government's SPS studies of the 1970s. Nevertheless, even if one plans to build 1,000 Solar Power Satellites, a greater degree of modularity will still result in a lower levelized cost of electricity, down to the cost-of-materials threshold just mentioned. Even with large constellations (i.e., greater than 100 SPS platforms), module sizes of 10MT-20MT or greater imply hardware costs 5- or 10-times higher than hyper-modular architectures.

Closing Observations

Reducing the currently high cost of space systems hardware is essential to a wide variety of ambitious future space goals – including, but by no means limited to, Solar Power Satellites. There appear to be no fundamental barriers to accomplishing this objective; however, the architectural approaches that we use for space systems must change if costs are to be reduced. The most important step on this path is decomposing the implementation of large space program objectives into modular, mass-produced system elements.

By way of example, within a couple of years of the completion of development, the Boeing Company had achieved production levels of some seven 787 aircraft per week (May 2013), with the goal of reaching ten per week by the end of the year.[23] The Boeing 787 has a dry mass of about 160-180 MT, and a unit cost (depending on the version) of between $210-$240 Million; i.e., a cost per kilogram of approximately $1,300 / kg. From a single major company, this advanced aerospace system manufacturing effort (even if at the larger scale) will realize production on the order of 2,000 MT of hardware per year; i.e., equivalent to about 4-times a large SPS demonstrator, or about one full-scale SPS every five years. These costs are too high for commercial SPS – which is the dilemma for architectures with large modules – but the direction is the right one: the challenge of manufacturing Solar Power Satellites at low cost is one that can be overcome.

Now it is time to turn our attention to the next most critical barrier to the successful realization of economically viable Solar Power Satellites: the challenge of low-cost space transportation.

[6-1] Some individuals in the aerospace community believe that the cost of access to space is the greatest challenge facing the realization of SSP; I disagree. Until the costs of Solar Power Satellite are slashed drastically, there will never be a *reason* to reduce the costs of space transportation. Hence, the situation is – and has been for years – a classic "chicken-and-egg" dilemma. I decided some years ago that so long as the basic architecture of space systems is monolithic, the cost of an SPS would always be astronomically high. Conversely, numerous studies have shown that, regardless of the specific payload, low-cost launch is technically achievable as long as there is a sufficiently large market.

[6-2] To be clear: the dollar values shown in Table 6-1 are (generally speaking) prices, not costs. All include profit for the companies that built these systems, and/or their parts.

[6-3] The data were drawn from various websites; specific references are not provided. However, the masses (weights) and costs are averages and not related to any particular product. Also, the costs shown are actually published prices; true marginal cost data are not available, but may be "guesstimated" as roughly 30%-50% of prices…!

[6-4] The costs in Table 6-1 are in US Dollars (2013).

[6-5] "Delta-IV Heavy" class implies a payload to LEO of roughly 20,000 kg-25,000 kg.

[6-6] This "composite unit count" is a rough estimate only. The actual vehicle manufactured by Boeing uses a common core with three (3) copies per vehicle, plus commonality with lighter versions in fabrication of Delta IV hardware, and with other vehicles.

[6-7] All of the weights, or more properly the masses, given in this book are expressed in terms of kilograms (a.k.a., "kg"), where 1 kg = 2.2 pounds (approximately).

[6-8] Few consumers expect to buy a personal computer (PC) with two batteries just in case one fails. If a battery fails, they take the PC back to store. Such services aren't available in space, except at the ISS.

[6-9] Contracting with the "lowest bidder" sounds very attractive; however, two arguments militate against this approach. First, you get what you pay for; and, second, once a specific vendor gets the contract to develop a "one-of-a-kind" or time-critical space systems project, the consequences of cancelling the contract are so dire to most programs that there is little the customer can do if costs rise significantly beyond the initial low estimates. (Not surprisingly, some competitions have been won by firms that low-ball their initial estimates to win the contract, while planning to "get well" once they have won.)

[6-10] "Nom de guerre" is a French phrase meaning roughly one's "Name used in War." This is rather fitting given the frequent and substantial cost overruns that occur in US DoD programs.

[6-11] As I recall, in the 1980s one phrase that was occasionally used to justify more or less arbitrarily reducing formally estimated costs – not actual costs – was "just to sprinkle some automation and robotics" on the problem. This approach and other superficial ideas are not discussed in this Chapter.

[6-12] It was also known as "better, faster, cheaper," etc. For a while, the idea was to "darken the skies" with small, inexpensive spacecraft. Unfortunately, this emphasis on many smaller missions at lower costs did not survive beyond the 1990s.

[6-13] Reference: Gruhl, W., "Lessons Learned: Cost/Schedule Assessment Guide for Non-advocate Review Teams" (presentation package; NASA Headquarters, Cost & Economic Analysis Branch, Office of the NASA Comptroller) c. 1987-1988.

[6-14] See: Sarsfield, Liam, "The Cosmos on a Shoestring: Small Spacecraft for Space and Earth Science," (RAND, Critical Technologies Institute Santa Monica, California). 1998. The data shown are for planetary spacecraft, not Earth orbiting spacecraft.

[6-15] Both Figures 6-1 and 6-2 are generalizations of much more detailed data sets. Figure 6-1 derives from a NASA viewgraph presentation by W. Gruhl in 1987. Figure 6-2 is based on data I developed from various sources in the mid 1990s.

[6-16] See: Yeh, S. and Rubin E.S., "A Review of Uncertainties in Technology Experience Curves," (Journal of Energy Economics, Vol. 34 (2012) pp 762-771; see: http://www.elsevier.com/locate/eneco). November 19, 2011.

[6-17] Various names have been applied to Thomas Wright's initial concept of a "Progress Curve", including "Learning Curve", "Experience Curve (used here); "Learning-by-Doing", etc.

[6-18] Oddly, in a September 2009 article, the *Economist* magazine incorrectly attributed the original idea of the "Experience Curve" to the Boston Consulting Group (BCG). While BCG certainly extended the idea with their research in the 1960s, but they did not originate it.

[6-19] If you don't recall hearing about "the Goldilocks Rule" before, don't worry about it: I created the term for the phenomenon described above and this is its first published use.

[6-20] This calculation assumes a total hardware lifetime of about 20 years.

[6-21] Although not the subject of this book, I would like to observe in passing that the same statement can and should be made about various other highly ambitious goals for government and commercial space missions and markets, including lunar outposts, space resources development, human Mars missions and others. Hardware cost for all of these could be reduced dramatically by the introduction of novel architectures that follow these principles and the application of technologies already in the laboratory or in use here on Earth.

[6-22] The analysis that underpins the findings presented in Figure 6-5 was very high-level at best; it was by no means a formal comparative cost estimate for various types of Solar Power Satellites; such an analysis is needed, of course. However, it is an internally consistent systems analysis, with certain assumptions that drove the results. These assumptions include: (1) a learning curve of 0.7; (2) an assumed reduction in the development cost per kilogram of a factor of 1.8 for each 10-fold increase in the total dry mass of the "module" to be developed; and (3) and assumed mass penalty for integration of modular systems of 10% for

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each 10-fold decrease in the size of the SPS module to be developed. [Concerning the latter assumption, in other words, in the case of a fully monolithic SPS (at the far right of the Figure), there is zero penalty, for a platform comprising 10 modules, there is a 10% penalty, for a platform comprising 100 modules, there is a 10%+10%=20% penalty, and so on].

[6-23] See:
http://www.chicagotribune.com/business/breaking/chi-boeing-787-production-20130509,0,4336931.story and
http://en.wikipedia.org/wiki/Boeing_787_Dreamliner

Chapter 7
Low-Cost Space Transportation

> *"It is apparent to me that the possibilities of the aeroplane, which two or three years ago were thought to hold the solution to the [flying machine] problem, have been exhausted, and that we must turn elsewhere."*
>
> *Thomas Edison (1895)*
> *American Inventor*

Overview

Logistics and the cost of deploying platform hardware – second only to the cost of manufacturing – are the most crucial issues to be resolved in the economics of Space Solar Power. A decade ago, typical costs to launch large payloads to low Earth orbit (LEO) ranged from \$20,000 to \$40,000 per kilogram or more, while costs to reach geostationary Earth orbit (GEO) were even higher, ranging from \$50,000 to \$100,000 per kilogram.

As we will discuss, progress since then has been modest but meaningful. This is essential: unless this problem can be solved, there is no hope that solar power harvested in space and delivered to Earth will ever be economically viable. Fortunately, significant improvements may be realized in the foreseeable future. First, the technologies and new systems needed for low-cost space launch are being developed by several organizations. Second, the new strategic SPS architecture represented by SPS-ALPHA and others like it should make it possible to finally resolve the decades-old "chicken-and-egg" conundrum of space transportation: which comes first, the market or the launch vehicle? And, finally, the key technologies for affordable in-space transportation required for SPS-ALPHA have already been proven.

Within SPS life cycle costs (LCC), there are four broad contributions from space transportation: the initial cost of Earth-to-orbit (ETO) transport, the cost of in-space transportation for initial deployment, and the recurring costs for both.[1] Of these four, the most important are the first two: initial ETO transport with affordable in-space transportation (AIST) a close second. Because these costs occur before the platform begins generating revenue, they loom large in any financial analysis. (Although recurring costs certainly must be kept low, revenues in the economics of a Solar Power Satellite can offset costs incurred during operations.)

These challenges are the primary topics of the Chapter that follows. The discussion first examines the requirements for SPS transportation then asks this key question: can this problem be solved? (I believe the answer to that question is "yes," not too surprisingly.) Finally, some prospective solutions will be examined. First, however, it's important to take a moment to review the physics of space transportation.[2]

The Physics of the Problem

The critical physics for space transportation of almost all types is embodied in what is known as the "rocket equation." This equation expresses the mathematical relationship among the initial mass and the final mass of a rocket-propelled object ($M_{initial}$ and M_{final}, respectively), the change in velocity experienced by the object (known as "Δv," which is read aloud as "delta-v"), and finally, the specific impulse produced by the rocket and a term to normalize the units, Earth's gravity – Isp and g, respectively.[3] The "rocket equation" is an exponential formula that reads:

$$\textit{Mass Ratio} \qquad \frac{M_{initial}}{M_{final}} \qquad e^{(\Delta v / Isp * g)}$$

The "Mass Ratio" has two components: "$M_{initial}$" divided by "M_{final}"; these are defined as follows. The initial mass – "$M_{initial}$" – which for any rocket comprises four constituents: (a) the weight of the vehicle, (b) the weight of the payload (if any) being carried by the vehicle, (c) the weight of the propellant to be consumed in the maneuver, and (d) the weight of residual propellant (if any) that may be left after the rocket-propelled maneuver is completed. In turn, the final mass – "M_{final}" – of the rocket comprises three constituents: (1) the weight of the vehicle, (2) the weight of the payload (if any) being carried by the vehicle, and (3) the weight of residual propellant (if any) that may be left after the rocket-propelled maneuver is completed.

The change in velocity – the "Δv" term in the rocket equation – is related to how much kinetic energy must be delivered by the combustion of the fuel. For example, the total change in velocity needed to launch a vehicle from Earth to low Earth orbit (LEO) is approximately 9,500 meters per second.[4] This total "Δv" comprises mostly the difference between the initial velocity and the final velocity, but also includes factors such as atmospheric drag and what are called "gravity losses" during the launch. "Delta-v" also depends on the latitude of the site from which the rocket is launched. (The closer to the equator, the smaller the "Δv" because the rotation of Earth increases the initial velocity of the rocket before launch.)

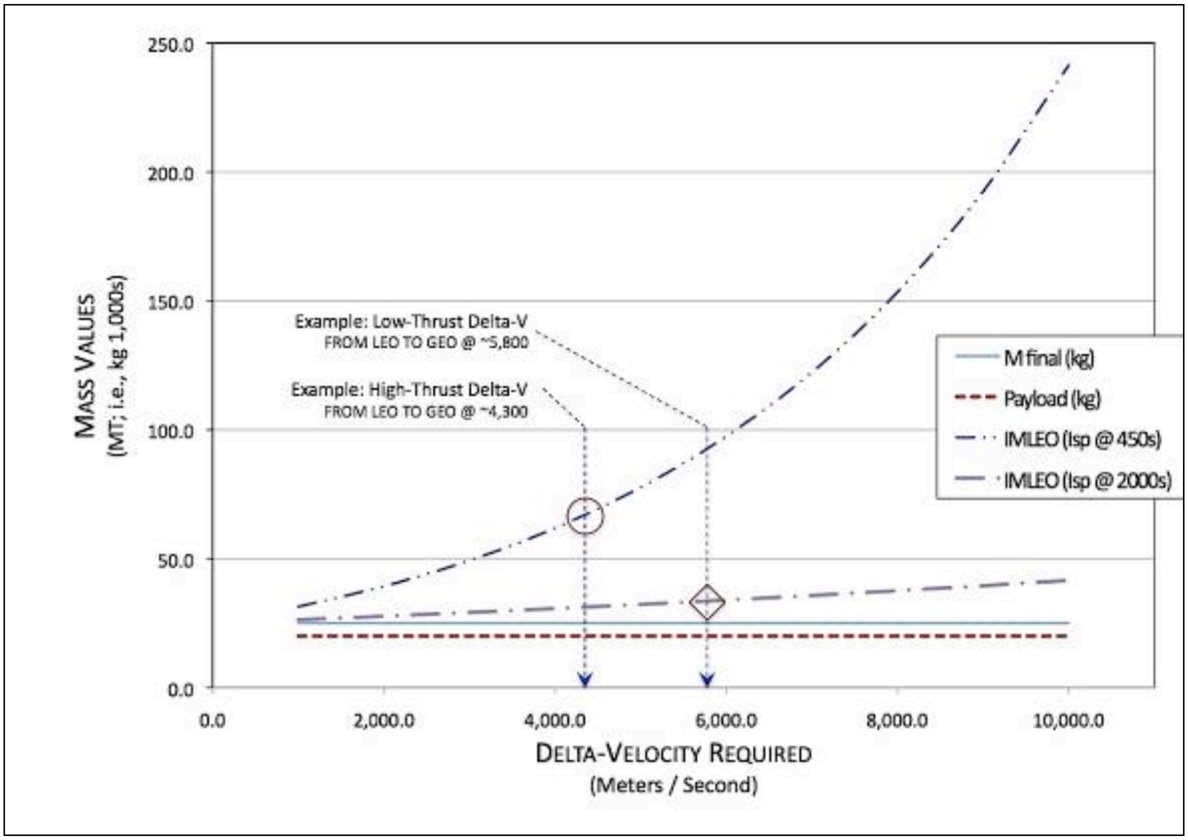
The specific impulse – "Isp" – is a reflection of the propulsion technology being used; it has to do with the fuel efficiency of the propulsion system and represents the change in momentum of the total mass (including vehicle, payload, etc.) per amount of propellant consumed by the rocket. Table 7-1 on the page following summarizes the Isp values for several rocket engines of potential interest for SPS space transportation.

The final term in the exponent of the rocket equation is an acceleration term: "g" – the quantitative value of the gravitational pull of Earth – namely, about 9.8 meters per second per second.[5]

Figure 7-1 on the next page illustrates what the rocket equation means; it depicts the variation in the initial mass in LEO (IMLEO) in metric tons (MT), including vehicle, payload, and fuel versus changing "Δv" (i.e., Delta-velocity, or the energy required). Two cases are shown in the figure: a high thrust case, where the Isp is about 450 seconds, and a low thrust case, where the Isp is around 2,000 seconds. In both cases shown, the LEO-to-GEO payload is assumed to be 20 MT; also – and quite artificially – the hardware mass of each type of vehicle is assumed to be 5 MT. Although this is not a rigorous analysis, it illustrates the main point: higher fuel efficiency (Isp) is extremely important in reducing the mass of the propellant required in low Earth orbit.

In addition to the rocket engine options for SPS space transportation described in this chapter, there are also technology options that do not involve rocket propulsion. The most familiar of these is the option of "aero-braking" or "aero-entry" in which a thermal protection system (TPS) like the ceramic tiles on the underside of the US Space Shuttle would be used to decelerate a vehicle by means of friction with the atmosphere of Earth, or Mars, or some other planet. (The several relevant technology options are discussed later in this Chapter.)

Figure 7-1 Illustration of the Impact of the Rocket Equation



Credit: Artemis Innovation Management Solutions LLC, 2013

Table 7-1 below summarizes the “Δv” – the change in velocity – for a number of different space transportation maneuvers relevant to SPS and different types of technologies. In the second column of the table, the Δv cases are all “high-thrust,” meaning that they involve propulsion systems with enough force to overcome the gravity losses (i.e., the pull of gravity) and launch a vehicle into orbit. However, they are relatively poor in fuel efficiency. The second column presents cases that are high in fuel efficiency, but are “low thrust,” meaning that they cannot be used for ETO transportation (the thrust they produce is too low to overcome the pull of gravity at Earth’s surface).

The Δv requirements for these two cases (i.e., high-thrust and low-thrust propulsion) differ due to gravity losses, which we discussed previously; however, the differences in propellants consumed are much more significant. As depicted in Figure 7-1, even though the Δv required for a low-thrust option (the diamond in the figure) is higher than the Δv required for the high-thrust option (the circle in the figure), the propellant required for the high-thrust, low-Isp case is much higher than that for the high-Isp case. The final column in Table 7-1 presents two aerobraking (or aeroentry) cases – a technology that (of course) can only be used when a vehicle is returning to Earth or to low Earth orbit, as reflected in the table.

Table 7-1 Comparison of "Δv" for Various SPS Space Transport Requirements[6]

Transfer Maneuver	**Delta-V (Δv) for High-Thrust Propulsion**	**Delta-V (Δv) for Low-Thrust Propulsion**	**Aerobraking (A/B) / Aeroentry (A/E)** Return from GEO / LEO
Earth-to-LEO (ETO Launch)	~ 9,500 m/s	n/a	n/a
LEO-to-GEO (In-Space)	~ 4,300 m/s	~ 5,800 m/s	n/a
GEO-to-LEO (In-Space)	~ 4,300 m/s	~ 5,800 m/s	< 3,000 m/s (approx.) (plus A/B Mass @ ~15%)
LEO-to-Earth (ETO Return)	n/a	n/a	< 9,500 m/s (plus A/E Mass @ ~15%)

Figure 4-5 in Chapter 4 presents a more complete 'map' of the energy requirements (i.e., Δv) for various maneuvers in space transportation – including transport from Earth to LEO and from LEO to GEO. You may have noticed in these figures that in many cases (including LEO to GEO transport) two values of Δv are identified. This has to do with the fact that *low-thrust* propulsion systems take longer to perform a maneuver and, as a result, more of the energy from the propellant goes into fighting what are known as "gravity losses."[7]

In summary, then, the physics of rocket propulsion teaches that only high thrust propulsion may be used for ETO transportation, and that highly fuel efficient (i.e., high Isp) propulsion is preferred for space transportation, even though it may be low thrust.

SPS Space Transportation Requirements

For many space transportation concepts, mission requirements may be divided neatly into those for ETO transport and those for in-space transport; in this case, a payload would be transported first to LEO and subsequently from LEO to GEO. There are alternatives, of course; some launch vehicle concepts would release their payload below LEO, and rely upon another system to transfer that mass to LEO. (A LEO-based rotating tether concept known as a "Skyhook" is of this type.) Other approaches transport payloads directly from Earth beyond LEO to what is known as a "GEO transfer orbit" (GTO).[8] Of these variations, we will focus on the first – ETO launch to LEO – which can be used in combination with a high-efficiency reusable in-space orbit transfer vehicle (OTV) to affordably transport hundreds to thousands of individual SPS payloads to GEO.

ETO Requirements for SPS

The topic of ETO transportation is an enormous one, spanning numerous systems concepts, diverse technology alternatives and various prospective market scenarios. Beginning in the 1970s, ETO transport at times has been examined by various SPS studies. Candidate solutions have ranged from extremely large reusable launchers to large expendable vehicles to smaller scale highly reusable launchers. The latter, smaller launch options have been considered beginning with NASA's SSP Fresh Look Study in 1995-1997, when such vehicles were enabled by the highly modular, robotically assembled SPS architectures first developed at that time.

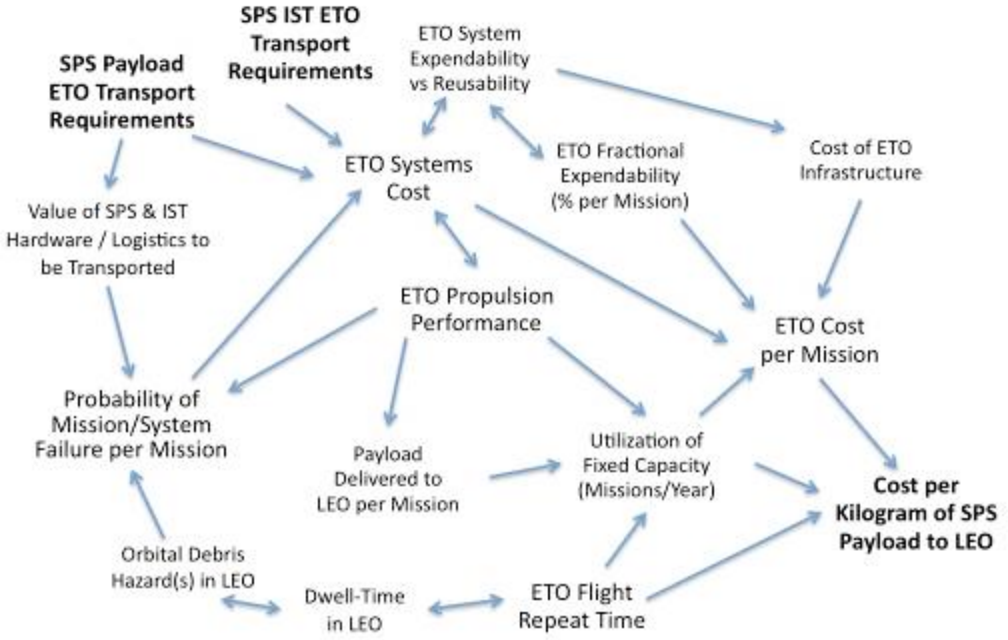
Unfortunately, the treatment of this critical topic was relatively modest in both the 2008-2011 International Academy of Astronautics (IAA) assessment of SSP and in the 2011-2012 NASA Innovative Advanced Concepts (NIAC) program-sponsored study of the SPS-ALPHA concept. The focus of both efforts was on SSP systems *per se* due to the limited duration and scope of each study. Still, even though considerably more analysis and technology development are needed, it is still possible to summarize the requirements that must be met by ETO systems to meet the needs of deploying modular Solar Power Satellites.

An ETO system used to launch full-scale, commercially viable (and therefore modular) SPS platforms must fulfill the following high-level functional requirements. First, it must provide transportation to LEO at \$300-\$500 per kilogram or less. Second, launch to LEO of SPS piece parts must accommodate payloads of approximately 10-20 MT mass.[9] Finally, vehicle operations must be capable of not less than 500 to 1,000 launches per year for construction of each SPS platform (not necessarily from the same launch site). In meeting these requirements, several key technical trades must be performed to finalize the design of an ETO vehicle, including:

- Propulsion Performance, such as the
    - Thrust-to-Weight (T/W) and T/W design margin
    - Specific Impulse (Isp), i.e., the fuel efficiency
- Architecture Level Issues, such as the
    - Cost of SSP AIST transportation to be supported (particularly the cost of launching fuel for AIST systems)
    - Scope and cost of any supporting in-space infrastructure [e.g., in-space refueling depot(s), space assembly, maintenance and servicing systems for AIST, etc.)]
- For Reusable ETO Systems,
    - Fractional expendability of the hardware system per mission
    - Utilization of fixed capacity (i.e., roundtrip time from Earth to LEO, and/or the number of missions per year)
    - ETO Transportation System Lifetime
    - Probability of ETO mission/system failure
- Operations Related Issues, including
    - Operational hazards and/or issues (e.g., orbital debris in LEO, dwell time in LEO, etc.)
    - Mission operations and sustaining engineering labor costs
    - Supporting systems and infrastructure costs (e.g., supporting communications network costs)
- End-to-End logistics infrastructure and operations

Figure 7-2 provides a conceptual summary of these diverse issues and their interactions. For example, propulsion performance affects ETO costs; orbital debris in LEO increases the probability of mission failure; and so on.

Figure 7-2 ETO Transportation Systems Trade Space Interactions



Credit: Artemis Innovation Management Solutions LLC, 2010

How Low is Low Enough for the Cost of ETO? At a fundamental level, the minimum cost for ETO transport cannot be less than the cost of the energy required to achieve low Earth orbit. Assuming a change in velocity from the surface to LEO of approximately 9,000 meters/second, and a factor of 3:1 for thermodynamic efficiency (i.e., the ratio of the chemical energy in the fuel consumed *versus* the kinetic energy in orbit), for each kilogram in LEO the energy required is some 121,500,000 Joules – equivalent to a little more than 33 kilowatt-hours. At a price of 10¢/kilowatt-hour, this would be equivalent to a cost contribution of about $3.30 per kilogram. As a simple rule of thumb, this energy cost should be multiplied by a further factor of three in order to account for the energy required for LEO-to-GEO transportation. Hence, the total energy cost of transporting SPS materials to GEO should be (very) roughly $10 per kilogram. This is a comfortably low value: clearly, there is no fundamental barrier to affordable Earth-to-GEO transport in terms of the cost of the energy. However, there are significant challenges in the engineering of low cost access to space.

How low must ETO costs be in order to no longer be a major hurdle to commercially viable Solar Power Satellites? The requirement stated above is approximately $300-$500 per kilogram to LEO; the recent NIAC study demonstrated that launch costs in this range could result in SPS that can compete in selected commercial markets on Earth. (These results are discussed in a later Chapter.) Can launch costs in this range be achieved? As we will discuss, the answer is almost certainly "yes" – although obviously the lower the cost the better.

Let's turn next to the topic of SPS requirements for in-space transportation.

SSP In-Space Transportation Requirements

It has been said that "low Earth orbit is halfway to anywhere;" [10] and while this is certainly true in terms of energy, for most Solar Power Satellite architectures a better phrase might be "GEO or Bust!" As we discussed in Chapter 4, reaching a GEO or near-GEO orbit – and affordable in-space transportation to get there – are crucial for SPS deployment and operations economics. Affordability will only be possible if space transportation can be made reusable and ETO transportation of propellants for in-space transportation systems is low cost.

If it is to support SPS-ALPHA deployment and operations, an AIST system must satisfy the following primary functional requirements: (1) transportation from LEO to GEO at less than $500-$1,000 per kilogram; and (2) transportation of exceptionally large numbers of SPS system modules in several classes, such as pieces of the RF transmitter array (for assembly in GEO), with a handful of specific mass types, up to approximately 10 MT (including the option of multiple modules being combined for a single launch and transport to GEO flight). Key technical issues that must be resolved include:

- Propulsion performance, including
    - The Specific Impulse (Isp) of the propulsion system (i.e., the fuel efficiency)
- Architecture-level issues, including
    - Expendability vs. reusability of systems
    - The cost of supporting ETO transportation (particularly the cost of launching fuel for AIST systems)
    - Scope and cost of supporting in-space infrastructure [e.g., in-space refueling depot(s), space assembly, maintenance and servicing systems for AIST, etc.]
- For AIST systems that are reusable OTVs
    - Fractional expendability of the hardware system per mission

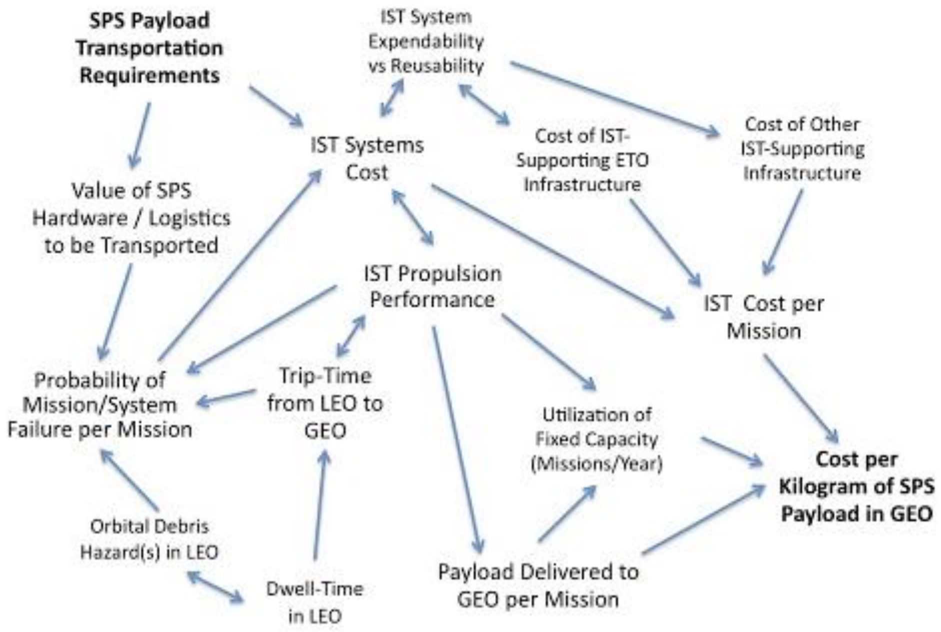
    - Utilization of fixed capacity (i.e., roundtrip time from LEO-to-GEO-to-LEO, or the number of missions per year)
    - System lifetime
    - Probability of mission/system failure
- Operations Related Issues, including
    - Operational hazards and/or issues (e.g., orbital debris in LEO, dwell time in LEO, etc.)
    - Mission operations and sustaining engineering labor costs
    - Supporting systems and infrastructure costs (e.g., supporting communications network costs)
- End-to-End logistics infrastructure and operations

In the long run, system options for in-space transportation of SPS hardware and logistics include a broad range of concepts, including: (a) expendable systems; (b) reusable vehicles using high-energy cryogenic propulsion; (c) reusable vehicles using solar electric propulsion; and (d) infrastructure-based in-space transport involving the use of systems such as space-based tethers. However, there are only a handful of potential systems options that are viable in the nearer-term; these include the following:

- AIST using high-thrust/high-energy chemical propulsion
    - This option typically involves short trip times, but also has relatively high requirements for fuel consumption
    - This might involve either expendable (one-way) or reusable (round-trip with refueling) systems options
    - Typically, this option would involve the use of cryogenic propellants [e.g., liquid oxygen (LOX) and liquid hydrogen (LH_2)]
- Reusable AIST using moderate- to high-power level solar electric propulsion (SEP).

Figure 7-3 provides a conceptual summary of these issues and their interactions. Just as was true for ETO (see Figure 7-2), in the case of AIST, propulsion performance impacts trip time and cost, utilization of fixed capacity is affected by payload per mission, and so on.

Figure 7-3 Affordable In-Space Transportation Trade Space Interactions



Credit: Artemis Innovation Management Solutions LLC, 2010

Some of the key factors that must be addressed in order to significantly improve the cost of in-space transportation for SPS deployment and operations include: Orbital Transfer Vehicle (OTV) hardware costs; OTV round-trip travel times; OTV propulsion fuel efficiency (i.e., specific impulse, or Isp); the costs of refueling reusable OTVs when needed; and Earth-to-Orbit transportation costs related to in-space transportation.

How Low is Low Enough for the Cost of AIST? Just as with ETO transport, a crucial question that must be answered is this: how low must in-space transportation costs be in order to no longer represent a major hurdle to commercially-viable Solar Power Satellites? As we saw above, the energy required for transportation from LEO to GEO is only a fraction of the energy required for ETO transport.

Fortunately, the transfer from low Earth orbit to geostationary Earth orbit is far more benign than the initial launch to LEO; as a result, long-lived reusable AIST systems should be tractable. Even with reusable vehicles, however, at a fundamental level the cost of in space transportation cannot be less than the ETO transportation cost of the propellant to be consumed in moving from LEO to GEO, and could be much greater.

So, given the above requirements – and the underlying physics of propulsion – how can the problem of space transportation for Solar Power Satellites be solved?

Space Transportation Technology Options

There is an array of technology options for SPS transportation; the primary considerations that matter at this level of discussion are three-fold: (1) the propulsion technology to be used, (2) whether the vehicle systems are expendable (used only once) or reusable (used many times), and (3) for ETO vehicles, the number of stages involved. Table 7-2 presents several general classes of propulsion-related technologies, including rocket engines and others.

Not all technologies apply to all phases of SPS transportation, of course. The propellant requirements for Options A and B are punishingly inefficient for LEO-to-GEO transportation. Conversely, Options E and G are irrelevant for ETO transportation. Aeroentry (Option D) is enabling for a reusable ETO vehicle's return to Earth, while aerobraking (Option E) is useful only for the return leg of a LEO-to-GEO transportation scenario. Table 7-3 summarizes the different primary options for ETO transportation for SPS systems. Table 7-4 presents the same sort of summary for AIST transportation for SPS systems. These options will be discussed in the section that follows ("*Can the Problem be Solved*"), with results from preliminary systems analysis results to support the discussion.

Table 7-2 Comparison of Isp for Various Propulsion Technologies[11]

ETO	In-Space	SPS Propulsion Technology	Specific Impulse (Isp)	Notes
✓		Option A Chemical Propulsion: Solid Rocket Motor	250 seconds	These are high thrust systems. This type of propulsion might be used for either ETO systems (particularly expendable launch vehicles or expendable upper stages), but are unlikely to be an affordable alternative for SPS in-space transportation
✓		Option B Chemical Propulsion: Hydrocarbon	350 seconds	These are high thrust systems; a bi-propellant approach such as Liquid Oxygen and RP (a hydrocarbon). This type of propulsion might be used for either ETO (expendable or reusable) or AIST systems (particularly expendable upper stages).
✓	✓	Option C Chemical Propulsion: Cryogenic	420-460 seconds	These are high thrust systems with reasonably good fuel efficiency; Liquid Oxygen (LOX) and Liquid Hydrogen (LH2) propellants may be used (the RL-10 is such a system). This type of propulsion might be used for either ETO or AIST systems (and for either reusable or expendable vehicles).
✓		Option D Aeroentry	Up to ~10,000 sec. (equivalent)	These are non-propulsive systems that use friction with the atmosphere a planet – such as Earth – to decelerate and thereby accomplish a change in velocity.

	✓	Option E Aerobraking	Up to ~10,000 sec. (equivalent)	These are non-propulsive systems that use friction with the atmosphere a planet – such as Earth – to decelerate and thereby accomplish entry into the planet's atmosphere.
	✓	Option F Electric Propulsion: Hall Effect Thruster	1,500-3,000 seconds	These are low thrust systems that require kilowatts of power or more; a typical propellant might include Xenon. This type of propulsion could only be used for AIST systems (and for either reusable or expendable vehicles).
	✓	Option G Electric Propulsion: Ion and/or Plasma Effect Thruster	5,000-20,000 seconds	These are very low thrust system concepts that require 100s of kilowatts of power or more; a typical propellant might include Hydrogen; the VASIMR thruster is such a system. This type of propulsion would be not usually be used for SPS AIST because the low thrust makes it very time-consuming for moving payloads from LEO to GEO.

For current materials and structures, the vehicle mass fraction for a reusable launch vehicle (RLV) remains unacceptably high, meaning that the vehicle itself is too great a fraction of the total gross lift off weight (GLOW), comprising the vehicle, its propellant and the payload, previously described as "$M_{initial}$". Because the vehicles (and their fuel) to be used for transportation in space must first be launched into Earth orbit, it is only reasonable to turn our attention first to the question of ETO transportation. This is the topic of the next several paragraphs. In addition to the options identified in Table 7-3, there are a number of alternative approaches, such as the use of a SEP stage to transport propellants to GEO that may be used for refueling a chemical propulsion or cryogenic propulsion vehicle.[12]

With the exception of plasma thrusters, all of the technologies listed in the previous table are available for application in space systems. Many have been used in various missions over the past several decades; others are well proven in ground tests, but have yet to be flown.

Table 7-3 Summary of SPS ETO Transportation Options

	SSTO (Single-Stage-to-Orbit)	**TSTO** (Two-Stage-to-Orbit)	**3STO** (3-Stage-to-Orbit)
Expendable Vehicles	•Technology Achievable, but Not Yet Available • Expected LEO Cost/kg: Low-to-Moderate	•Systems Now Available • Expected LEO Cost/kg: Moderate	•Systems Now Available • Expected LEO Cost/kg: Expensive
Mixed Expendable-Reusable Vehicles (e.g., Reusable Booster, Expendable 2nd Stage)	•N/A	•Technology Not Yet Achievable • Expected LEO Cost/kg: Low-to-Moderate	•Technology Achievable, but Not Yet Available • Expected LEO Cost/kg: Moderate
Reusable Vehicles	•Technology Not Yet Achievable • Expected LEO Cost/kg: Very Low	•Technology Not Yet Achievable • Expected LEO Cost/kg: Low	•Technology Achievable, but Not Yet Available • Expected LEO Cost/kg: Low-to-Moderate

There are a number of possible systems options, including the following: (1) existing expendable launch vehicles (ELVS); (2) new ELVs, perhaps dedicated to launching SPS; (3) new heavy lift launch vehicles (HLLVs), again perhaps dedicated to launching SPS; (4) new SPS-dedicated reusable launch vehicles (RLVs), including both moderate size and HLLV size payload vehicles; (5) new nearer-term reusable launch vehicles (RLVs), that serve multiple markets, including SPS (designated as "shared"); and (6) in the longer-term, new SPS-dedicated RLV that have longer lifetimes or higher performance than other RLV cases.

Table 7-4 Summary of SPS AIST Options

	Chemical Propulsion	Cryogenic Propulsion	Solar Energy Propulsion (SEP)	Aero-Entry (AE)/ Aero-Braking (A/B)
Expendable Stages	•ETO to LEO or GTO orbits •No Aerobraking (A/B) or Aeroentry (A/E) •Chemical Propulsion to GEO •Technology is Available • Expected GEO Cost/kg: Very High	• ETO to LEO or GTO •No A/B or A/E •Cryo to GEO •Technology is Available •Expected GEO Cost/kg: High	•ETO to LEO •No A/B or A/E •SEP to GEO •Technology is Available •Expected GEO Cost/kg: Moderate	•N/A
Reusable Orbital Transfer Vehicles (ROTVs)	•N/A	•ETO to LEO •Cryo to GEO •Technology is Available •Expected AIST Cost/kg: Low	•ETO to LEO •SEP to GEO •Technology is Available •Expected AIST Cost/kg: Very Low	•Chem or Cryo Propulsion to GEO •Technology is Available • Expected GEO-to-LEO Cost/kg: Low

Can the Problem Be Solved?

If SPS are to become economically viable in commercial baseload power markets on Earth, then it will only be due to the availability of extremely affordable Earth-to-orbit and in-space transportation systems. Can such systems be achieved? As I mentioned, it is my view that the answer to this question is “yes.” However, such a solution must not only be technically possible but also programmatically achievable. The foundation for solving both problems lies in realizing affordable transportation to LEO. There are three possible solutions to the problem: (1) very low-cost expendable launch vehicles (ELVs), (2) reusable launch vehicles (RLVs), or (3) some type of infrastructure-based approach to space launch.

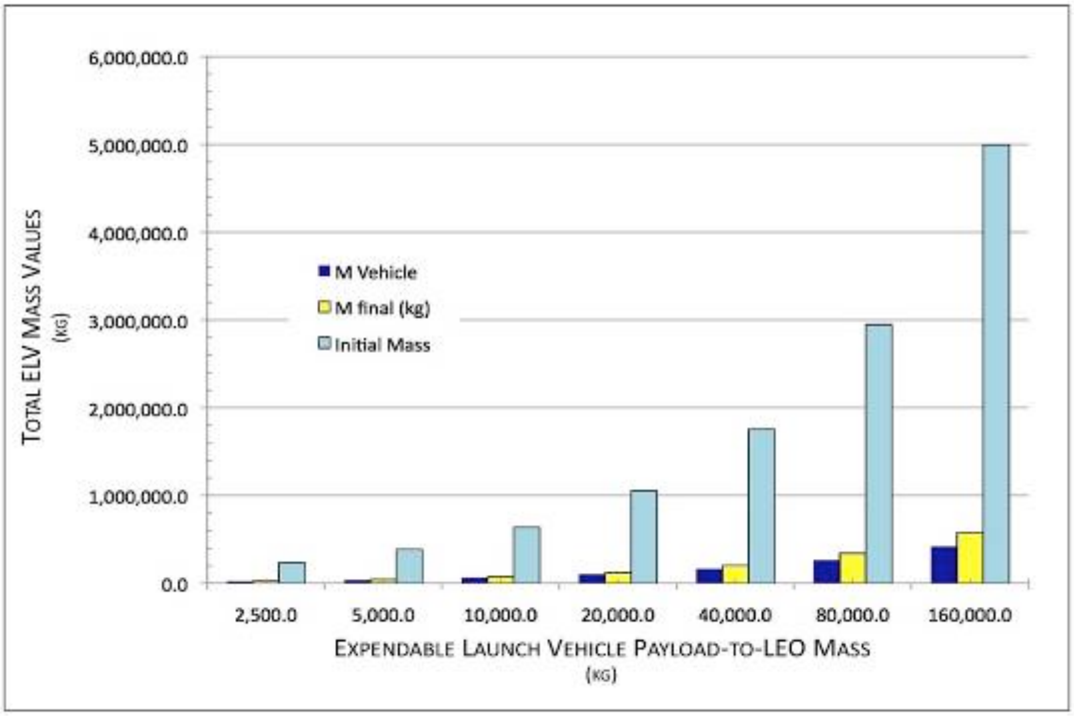
Earth-to-Orbit Transportation

The sections that follow examine the first two solutions for ETO transport: ELVs and RLVs, which represent near- and mid-term options, respectively. (Farther-term possibilities involving infrastructure-based approaches are discussed at the end of the Chapter.) If expendable launch vehicles were to be used to transport large SPS platform pieces and associated logistics to LEO, clearly the only way in which they might be affordable would be if the launchers (when mass produced) were cheap, really cheap. We spoke at some length about affordable space hardware in Chapter 6, focusing on the SPS platform itself. We can apply the same approach to consideration of ELVs for SPS transport to LEO.

Expendable Launch Vehicles. Let's suppose that a given ELV with a dry mass of roughly 64 MT and propellant load of about 560-570 MT is capable of placing a payload of some 10 MT in LEO.[13] For an SPS capable of delivering about 2 GW to Earth, let's assume a nominal mass of 20,000 MT. In this case, some 2,000 ELVs would be required to launch the initial SPS platform hardware. Referring to Chapter 6, obviously there will be a significant cost advantage in mass-producing this large number of vehicles. If the initial specific cost for this ELV is $20,000 per kilogram, then the cost per kilogram for 2,000 copies would be approximately $400 per kilogram, and the cost of each of the ELVs would be therefore roughly $25M. The hardware cost of the ELVs would contribute about $800M to the total deployed cost of the SPS platform.[14] For an SPS delivering 2 GW with a hardware mass of 20,000 MT, the ELV hardware contribution to the total cost of power would therefore be about $260 per Watt, and – over a 30-year lifetime – to the levelized cost of electricity (LCOE) of about 97¢ per kilowatt-hour. Even given the various contributors to LCC that have been neglected, this lower limit is much too high for Space Solar Power to be economically viable in terrestrial baseload markets.[15]

Is the size of the ELV payload the problem? Would it make a difference if the payload were larger – or smaller – than the 10MT assumed above? Figure 7-4 illustrates the results of a high-level systems analysis that examines the effect of changing payload mass on the total ELV mass over a range from 2,500 kg to 160,000 kg to LEO.

Figure 7-4 Effect of Changing Payload Mass on ELV Masses

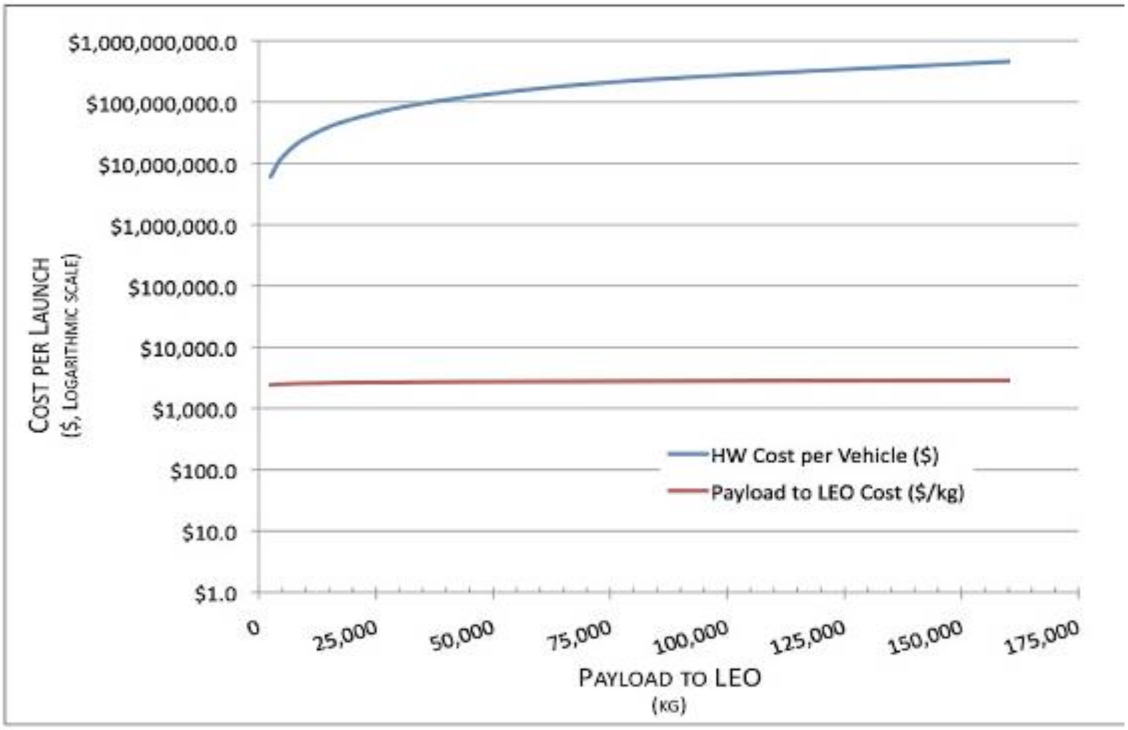


Credit: Artemis Innovation Management Solutions LLC, 2013

As shown in the figure, as the size of the payload increases for the same class of vehicle technology, the ratio of the payload mass to vehicle mass improves; in other words, with larger ELVs the total mass of the vehicle should decrease relative to the weight of the payload being launched. There is another advantage in going “big”; as we observed in Chapter 6, larger space systems tend to have lower costs per kilogram than smaller systems of similar technology and complexity. This should also be true for launch vehicles. In combination then, the amount of launch vehicle mass required to place a kilogram of payload in LEO drops with increasing size, and the cost per kilogram of the ELV decreases at the same time. This is one reason why many analysts have in the past advocated the use of heavy lift launch vehicles (HLLVs) for ambitious missions such as SSP. However there is another piece to the cost puzzle that we mentioned a moment ago: mass production of the launch vehicles.

As the size of the ELV and its payload increases, the initial cost per kilogram-payload drops. However, since the number of vehicles manufactured decreases because fewer are needed to launch a given SPS, then so will the cost benefit due to the "learning curve." As shown in Figure 7-5, all of these various factors – the payload mass fraction, the cost per kilogram for vehicle hardware, and the learning curve effects on costs – tend to balance out over a broad range of payload capacities.

Figure 7-5 Relationship Between Vehicle Cost and Payload Cost per Kilogram



Credit: Artemis Innovation Management Solutions LLC, 2013

As shown, although larger payloads use “less vehicle,” the cost per kilogram to LEO is surprisingly stable across a wide range of payload masses. (Note that the y-axis depicting “Cost per Launch” is presented on a logarithmic scale.) There were, of course, a range of different assumptions that went into this analysis; these included the value of the learning curve factor, the percentage improvement in mass fraction with increasing payload weight, the propulsion technology used, and so on. However, even with variations in these assumptions, the principal results are unchanged: even in huge numbers ELVs cannot deliver the very low costs to LEO that will be needed if SPS are to be economically viable. However, expendable launch vehicles can be cheaper when used in larger numbers and for narrower purposes in the development of SSP; we’ll return to that topic in a few moments.

For now, let’s consider the second major option for SPS ETO transportation; namely, Reusable Launch Vehicles.

The Limits of Reusable Launch Vehicles. The concept of very low cost RLVs for SPS launch has been examined several times during the past four decades. There are several major components in the cost of launch for an RLV payload to LEO. Two of the most important are the cost of the RLV itself (amortized over the number of times it can be used), and the cost of operational and sustaining engineering personnel for the total system. Following on the discussion of aerospace hardware costs in Chapter 6, the nominal cost to develop a national fleet of single-stage-to-orbit (SSTO) reusable launch vehicles (RLVs) of about 200 MT dry mass (which would be capable of launching roughly 20 MT to LEO) would depend on the number of vehicles fabricated and the number of times each vehicle can be used.

As illustrated in Figure 7-6, as the number of possible flights per vehicle increases, the cost contribution due to the original investment in the vehicle dry mass hardware decreases. (We've spoken of this before as "the utilization of fixed capacity".) As shown, if the vehicle has a mass of 100,000 kg, (i.e., 220,000 lbs.), and the fabrication cost of the hardware is $5,000 per kg, the payload to LEO is ~10,000 kg, and the vehicle can fly (without spares) some 200 times, then the minimum cost of the payload to LEO cannot be less than $1,000 per kilogram. To reach the goal of launch at not more than $200 per kg to LEO, then this vehicle must be capable of being used not less than 2,000 times – with minimal repairs! There is an obvious trade expressed here: if the manufactured cost of the vehicle is lower, then the degree of reusability may also be lower, and still achieve the goal of low cost ETO transportation. Conversely, if it is more expensive, then the degree of reusability must be even higher.[16]

Figure 7-7 addresses a second major component of ETO and life cycle cost: the cost per flight due to the labor-hours involved. In other words, the figure illustrates the cost contribution of the people who work in mission operations, refueling, launch operations, sustaining engineering, repair and maintenance, etc. As shown, for a vehicle launching 10,000 kg to LEO, the total labor hours per flight must be less than 10,000 hours, which (if the vehicle launches about once per week) can be stated as being less than 200 full-time individuals. Once again, there is an obviously trade here: if the payload can be increased without increasing the number of labor-hours, or the number of flights per year increased, then the cost contribution due to labor can be reduced.

Figure 7-6 Lower Limit on RLV Launch Cost Due to Vehicle Hardware

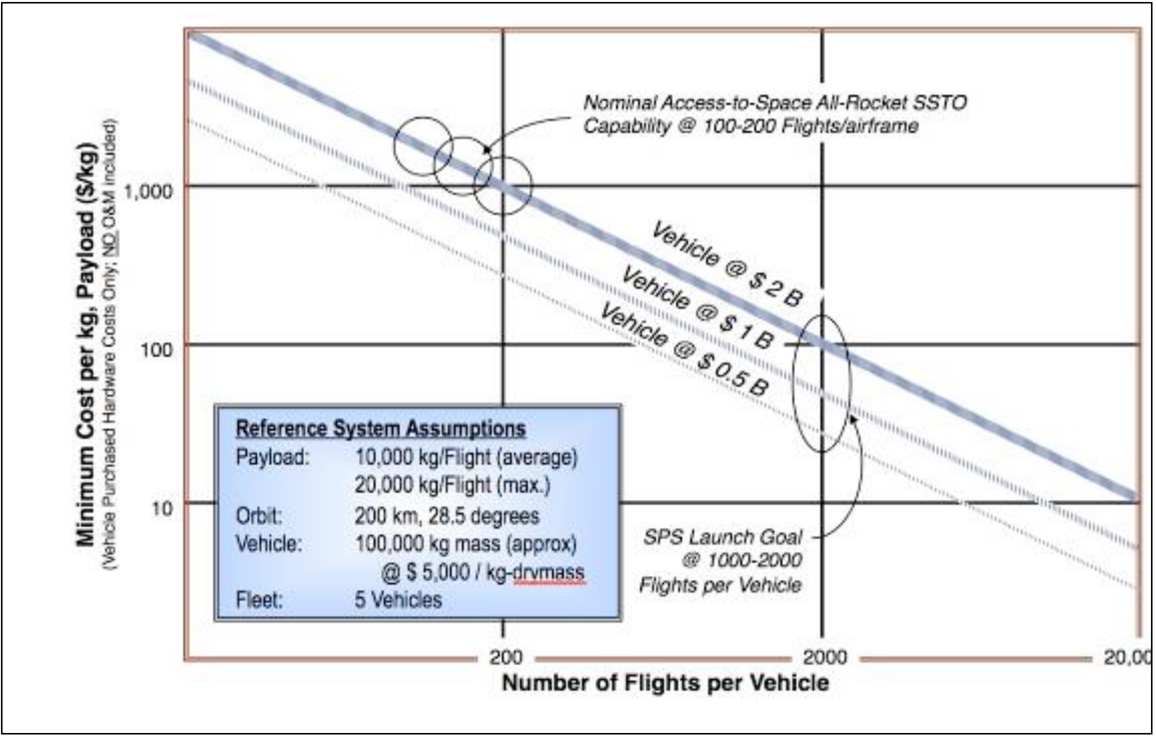
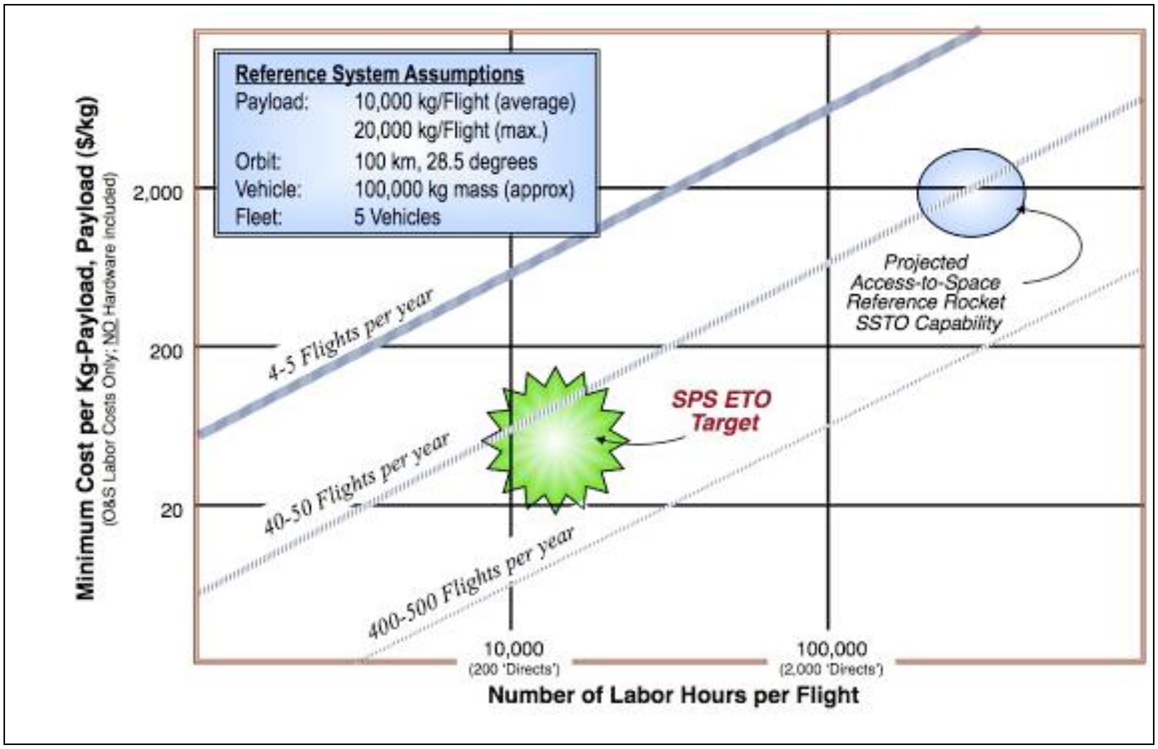


Figure 7-7 Lower Limit on RLV Launch Cost Due to Vehicle Operations Labor



In total, these high-level analyses imply (logically enough) that low-cost RLV systems must be both highly reusable and largely autonomous once operations begin. In addition, the analysis leads to the critical requirement for low-cost launch: high traffic rates.

Evaluating ETO Options[17]

As should be clear from the forgoing discussion, there are many possible ETO transportation and SPS platform options. We've looked in some detail at ELV and RLV options for launch of a full-scale SPS platform and found that RLVs are clearly required for economically viable based Space Solar Power delivered from large-scale Solar Power Satellites. However, what about nearer term milestones (such as SPS demonstrations)? Could these be accomplished without an RLV? Almost certainly the answer to this question is "yes." Let's compare some options.

As we've seen, there's a long list of different near-term options for SPS ETO transportation. These include:

- An existing ELV, shared with other markets;
- A new ELV, dedicated to launching SPS;
- A new RLV, either
    - Shared with other markets (moderate lifetime or long lifetime), or
    - Dedicated to launching SPS (moderate lifetime or long lifetime); and,
- A new Heavy Lift Launch Vehicle, of either the
    - Expendable type, or
    - Reusable type.

For the sake of simplicity in comparing these launch options, let's look at just two SPS platform scenarios (both assuming microwave power transmission): a moderate scale "pilot plant," capable of delivering approximately 10 MW to Earth, and a full-scale SPS, capable of delivering 1 GW to Earth. For both of these, we'll need to make common assumptions regarding the specifications of the system to be launched and the ETO systems themselves. The first assumption is that the system to be launched is a modular SPS for which the average module mass is 1,000 kg (i.e., about 2,200 lbs).[18] Second, all of the cases assume there is a common manufacturing curve for both ETO vehicle and platform/payload systems.[19]

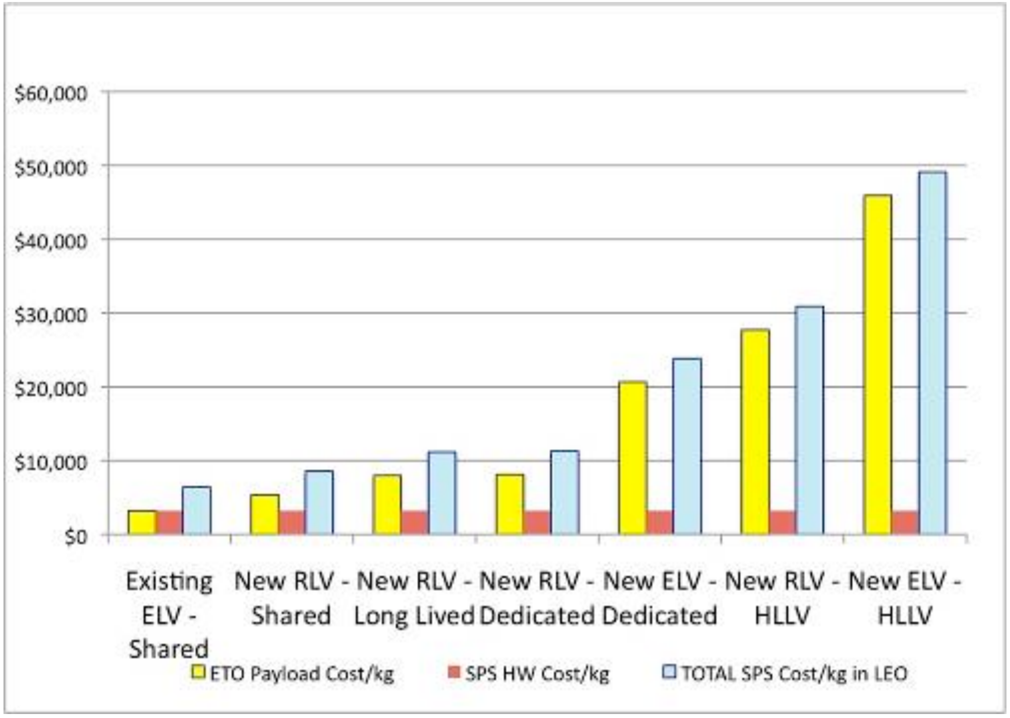
There are also some distinctions among the ETO options that must be taken into account. First, the initial cost per kilogram (based on the design, development test, and engineering; aka, "DDT&E") for the ETO and platform systems is assumed to be lower for the ETO vehicles than for the ETO platforms, and that ELVs are cheaper to develop than RLVs. (This is reasonable since expendable vehicles are in large measure structure and fuel tanks, which are cheaper than thermal protection systems, which are in turn cheaper than electronics and PV arrays.) Specifically, it's assumed that the cost per kilogram for the initial development of ELVs is about \$25,000 per kilogram, that the specific cost for development of RLVs is roughly \$50,000 per kilogram, and that the specific cost for development of SPS platform modules is \$100,000 per kilogram.

Finally, let's work with three different lifetime options for ETO systems. The first of these is obviously "single use," which applies to expendable launch vehicles. The second is a "nominal" lifetime for reusable launch vehicles, corresponding to a use of approximately 500 flights, with *fractional expendability* of 0.02% per flight. The final option is a "long-lived" option for RLVs, corresponding to a use of approximately 1,000 flights per airframe, with *fractional expendability* of 0.01% per flight.[20]

So, given all of these variations, how do the several launch options compare for the two SPS platform cases?

Moderate-Scale SPS Pilot Plant. In this case, the ETO market option is that of launching a moderate-scale SPS pilot plant, with a total platform mass launched to low Earth orbit of approximately 400,000 kg (400 MT, or about 880,000 lbs). Figure 7-8 presents the results of the initial analysis of the ETO options for the launch of this moderate-scale SPS pilot plant. In the figure, the x-axis lists the ETO options under consideration and the y-axis plots the estimated cost per kilogram for each option.

Figure 7-8 Launch Options for a Moderate-Scale SPS Pilot Plant (@ 400 MT)

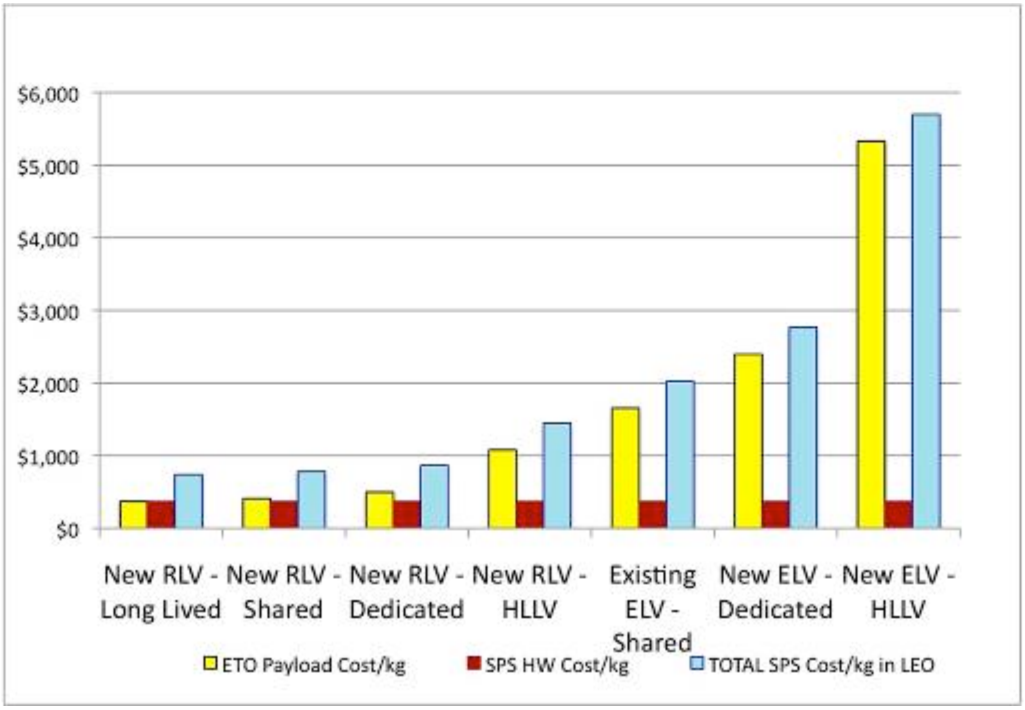


Credit: 2010 Artemis Innovation Management Solutions LLC

For this SPS platform case, the lowest cost launch solution is an existing ELV system shared with other markets. Roughly equivalent ETO systems would include a new RLV that was shared with other markets and a new, very long-lived RLV. The worst ETO launch solutions for this market option were the development of a new expendable HLLV or a new reusable launch vehicle in the HLLV class. The development of a new ELV dedicated to the launch of SPS was also a more expensive option than others. For all smaller scale SPS demonstrations such as those discussed in subsequent Chapters, existing ELVs are the lowest cost launch option.

A Full-Scale SPS Platform. What about launching a full-scale SPS? We've already seen that an RLV is needed, but how do the several options compare? Let's examine the launch of a single fully operational SPS, with a total platform launched to low Earth orbit (LEO) of approximately 12,000,000 kg (12,000 MT); Figure 7-9 presents an analysis of the ETO options. In the figure, the seven ETO options under consideration are listed along the x-axis; the y-axis reflects the estimated cost per kilogram based on several underlying assumptions.

Figure 7-9 Launch Options for a Single Full-Scale SPS (@ 12,000 MT)



Credit: 2010 Artemis Innovation Management Solutions LLC

Even a single full-scale SPS represents a dramatic increase in the total number of launches compared to demonstration pilot plants – and changes the results of our evaluation of launch options. For this market option, the best launch solution is a new long-lived RLV system, even if it is dedicated to SPS launch (This option gets even better if the vehicle is shared with other markets). Roughly equivalent ETO systems would include a new RLV shared with other markets as well as a new RLV dedicated to SPS launch that is not very long-lived. The worst ETO launch solution for this market option is clearly the development of a new expendable HLLV. At this scale of launch, expendability without extremely high manufacturing rates is no longer at all competitive.

However, the development of a new heavy lift RLV moves up in the ranking strikingly. Moderate payload (25 MT) class ELVs – although superior to an expendable HLLV – become increasingly expensive compared to other options. For the assumed launch of multiple SPS, heavy lift RLVs become the best ETO option – just as was found in the 1970s.

ETO Transportation Conclusions. Several conclusions can be drawn even from the high-level analysis presented here. The only way to achieve – in the nearer term – the exceptionally low cost launch required for economically competitive SPS will be through the development and deployment of reusable ETO transportation systems. In all cases, expendable heavy lift launch vehicles are the most expensive solution.

However, for early demonstrations and pilot plants, existing ELVs are clearly the most cost-effective launch system. As the planned number of SPS launches increases, then large payload RLVs of the type examined in the 1970s ERDA-NASA SPS studies become increasingly cost-effective.[21] However, the up-front investment required for these systems is quite large, suggesting that, for the initial launch of modular SPS, smaller RLVs are preferred and that longer lived reusable launch vehicles are lower in cost than shorter-lived systems.

Now let's turn our attention to the problem of getting from LEO to GEO.

Evaluating Affordable In-Space Transportation Options

There are two principal technology options for reusable in-space SPS transport: cryogenic orbital transfer vehicles (OTVs) and solar electric propulsion (SEP) OTVs.[22] Either of these can make a significant contribution to the installed cost of an SPS, and the cost of propellants needed for launching to LEO is the largest component of these. Another contribution comes from the OTV hardware itself. Some of the key cost-related figures of merit for SPS in-space transportation include:

- In-Space Transport Cost per Installed SPS Hardware unit Mass ($/kg)
- Specific Cost of the OTV Hardware (i.e., $/kg-OTV)
- Specific Mass of the OTV Hardware (i.e., kg-OTV/kg-SPS transported per flight)
- Number of OTV Roundtrip Flights to GEO per Year (i.e., #-OTV Flights/year)
- SPS Mass Delivered per OTV Flight to GEO (i.e., kg-SPS / OTV Flight)
- Number of Years in OTV Lifetime[23] (years)
- OTV Mass-Effectiveness Fractions
    - Mass of the OTV per Mass of the Fuel (i.e., kg-OTV / kg-Fuel)
    - Mass of the OTV *and* Mass of the Fuel per Payload Mass (i.e., kg-OTV plus kg-Fuel divided by kg-payload)

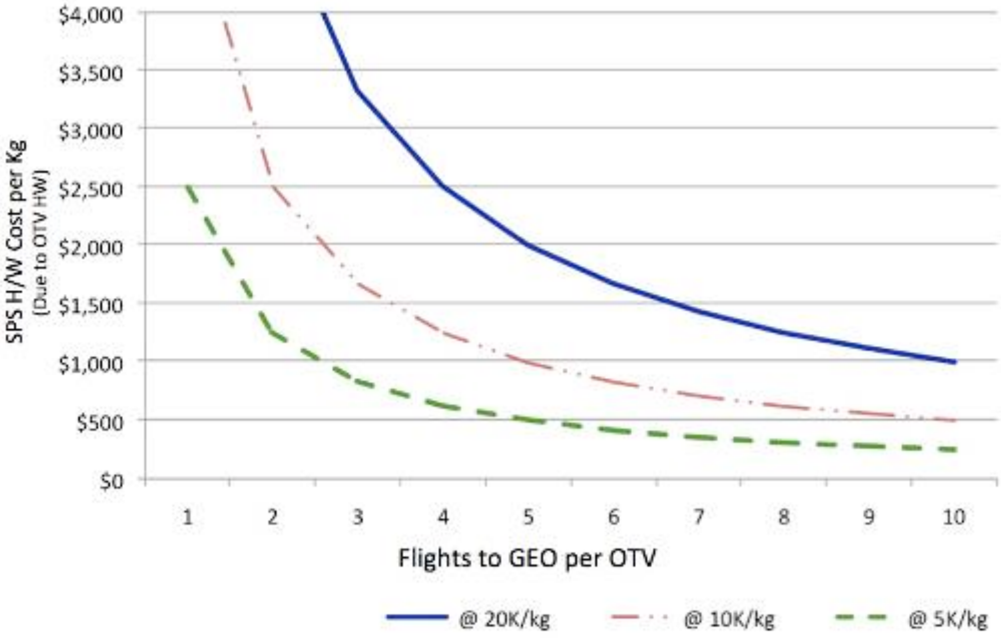
From among these variables, let's examine a straightforward limits analysis involving only the following three figures of merit: the cost per kilogram for the OTV system, the number of missions per OTV, and the kilograms for the OTV system for each kilogram of SPS hardware transported. For the sake of simplification here, the following very rough assumptions have been made:

- Cryogenic OTV: 2 kg of SPS Hardware per 1 kg of OTV Hardware, and
- SEP OTV: 5 kg of SPS Hardware per 1 kg of OTV Hardware.

Given these assumptions, Figure 7-10 illustrates the parametric relationships for a Cryogenic OTV and Figure 7-11 illustrates the relationships for a Solar Electric Propulsion (SEP) OTV. Three cases have been examined for both types of OTV: (1) the OTV HW costs $20,000 per kilogram; (2) the OTV HW costs $10,000 per kilogram; and (3) the OTV HW costs $5,000 per kilogram.

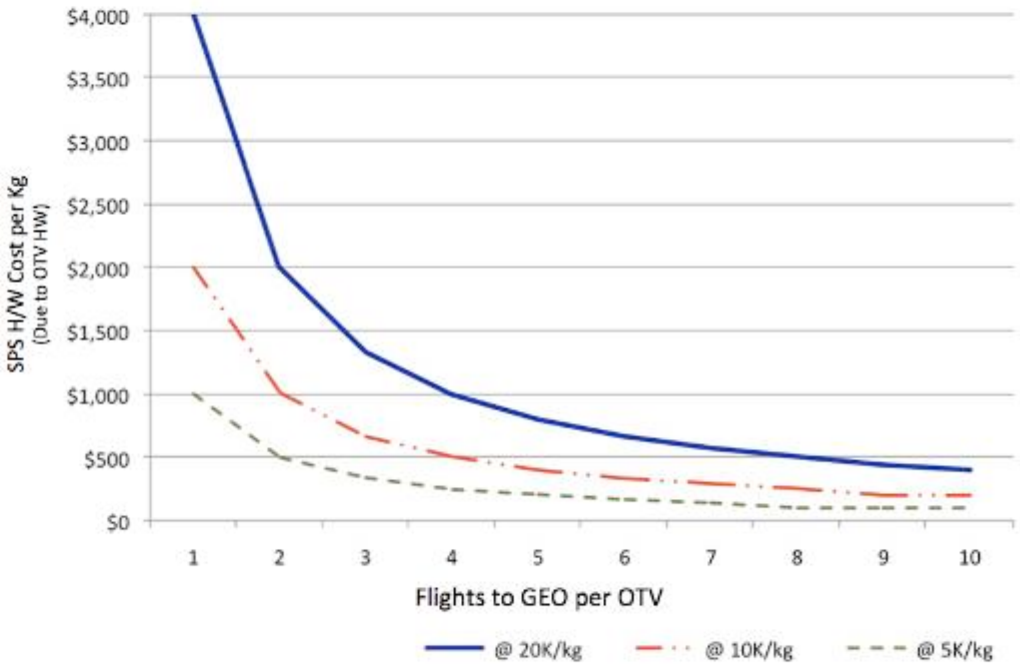
Given the assumptions indicated above, in the case of an expendable cryogenic OTV (used only once), it is clearly impossible for the cost contribution to the installed SPS HW cost per deployed kilogram to be less than $2,500 per SPS kilogram. For a reusable Cryogenic OTV, it is clear that the cost of the OTV is critical to achieving an acceptable cost per kilogram for the SPS hardware, even with 10 flights per OTV. Only when the OTV hardware cost is $5,000 per kilogram or less is the SPS HW cost $250 per kilogram or less. Although not shown in the figure, for 20 flights per reusable OTV, the cost performance improves and an OTV with a specific cost of $10,000 per kilogram or less can result in SPS HW cost $250 per kg or less.

Figure 7-10 Cryogenic OTV HW Cost Contribution to Installed SPS HW Cost



Credit: Artemis Innovation Management Solutions LLC (2013)

Figure 7-11 SEP OTV HW Cost Contributions to Installed SPS HW Cost



Credit: Artemis Innovation Management Solutions LLC (2013)

In the case of an expendable SEP OTV (used only once), the cost contribution to the SPS HW cost per deployed kilogram cannot be less than $1,000 per SPS kilogram. For a reusable SEP OTV, the HW cost of the OTV is also important to achieving an acceptable cost per kilogram for the SPS hardware. In the case of 10 flights per OTV with OTV hardware costs of up to $20,000 or less, the SPS HW cost will be $500 per kilogram or less. In the case of an SEP OTV of $5,000 per kilogram or less, the cost contribution is $100 per kilogram or less. Although not shown in the figure, for 20 flights per reusable OTV, the cost performance improves still further. The contribution to the cost per kilowatt-hour of SPS-delivered energy due to OTV hardware costs discussed here can be calculated based on the figures of merit (FOMs) identified above.

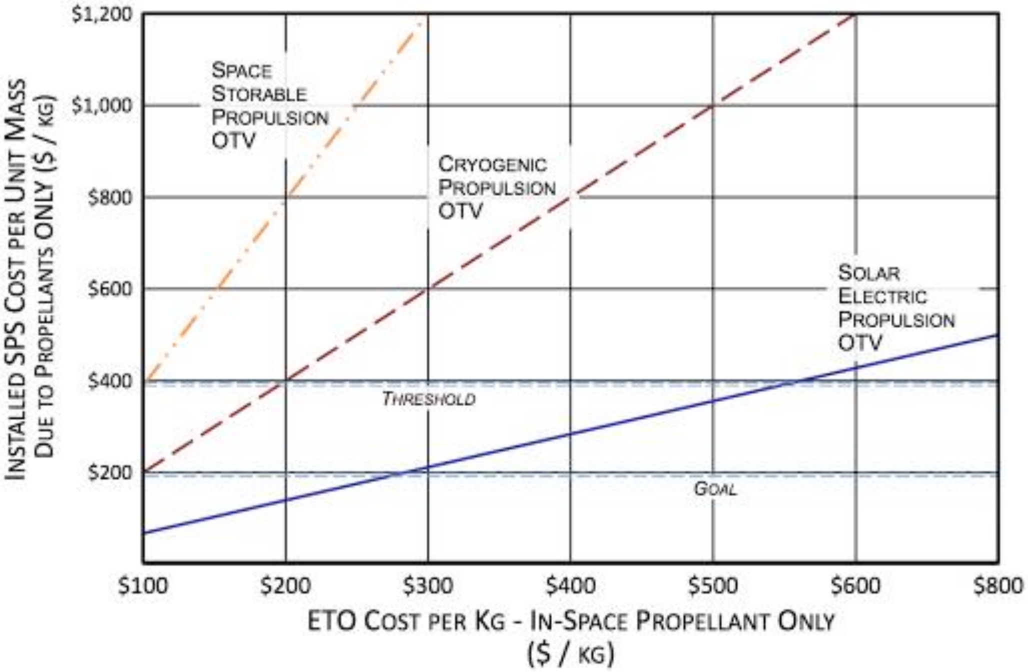
Now, what about another key FOM for in-space transportation, namely, the mass of the fuel consumed by an OTV in transferring SPS payloads from LEO to GEO?

As we discussed at the beginning of this chapter (See Figure 7-1), the lower the fuel efficiency (i.e., the Specific Impulse or "Isp") of an orbital transfer vehicle, the more propellant will be consumed for a given maneuver. Although low-thrust electric propulsion vehicles suffer from greater gravity losses (because it takes longer to make the maneuver), the higher Isp enables these systems to use far less fuel than other types. The use of fuel is a huge driver of the installed SPS cost because all of the fuel to be consumed must first be launched to LEO by the ETO transportation system. Figure 7-12 illustrates this point with three cases: a space storable OTV, a cryogenic propulsion OTV, and a solar electric propulsion OTV. (As I've noted earlier, this is <u>not</u> a rigorous analysis, but it is roughly correct and internally consistent.)

As illustrated, the main point is clear: the higher fuel efficiency solutions are the only real prospect for Space Solar Power to be affordable. Lower efficiency solutions consume far too much expensive propellant, even if the vehicles themselves are reusable.

In-Space Transportation Conclusions. The results of this discussion are two-fold. First, there are viable in-space transportation solutions for SPS; these are reusable vehicles. The most likely candidates are those involving high-efficiency propulsion, such as solar electric propulsion. Also, for in-space transportation (as was the case for ETO transport) the cost of the vehicle and the number of times it may be reused are key discriminators, but the cost of propellant is dominant. In-space transportation doesn't play a role in LEO demonstrations. However, from the initial SPS pilot plant in GEO, high-efficiency reusable OTVs are the best option for the nearer term.

Figure 7-12 LEO-GEO Propellant Cost Impact on Installed SPS HW Cost



Credit: Artemis Innovation Management Solutions LLC

Now, let's turn take a look at some the specific solutions that might be used during the coming decades.

SPS Space Transportation Solutions[24]

All in all, the transportation requirements for Solar Power Satellites are challenging, but by no means unachievable. As we discussed earlier, reusable systems are necessary for full-scale SPS economics; however, ELV launchers are the least expensive solution for sub-scale SPS pilot plants. If such a platform is to be deployed to GEO, advanced technology reusable in-space transportation (e.g., SEP OTV) will be required.

Assuring and improving access to space has been a priority for the US and other countries since the 1950s. The early development of the ballistic missile and related expendable launch vehicles in the 1950s and 1960s led in the 1970s to the development of the first (partially) reusable launch vehicle: the US Space Shuttle. These developments were paralleled by the emergence of various new expendable launchers in other countries (e.g., for former Soviet

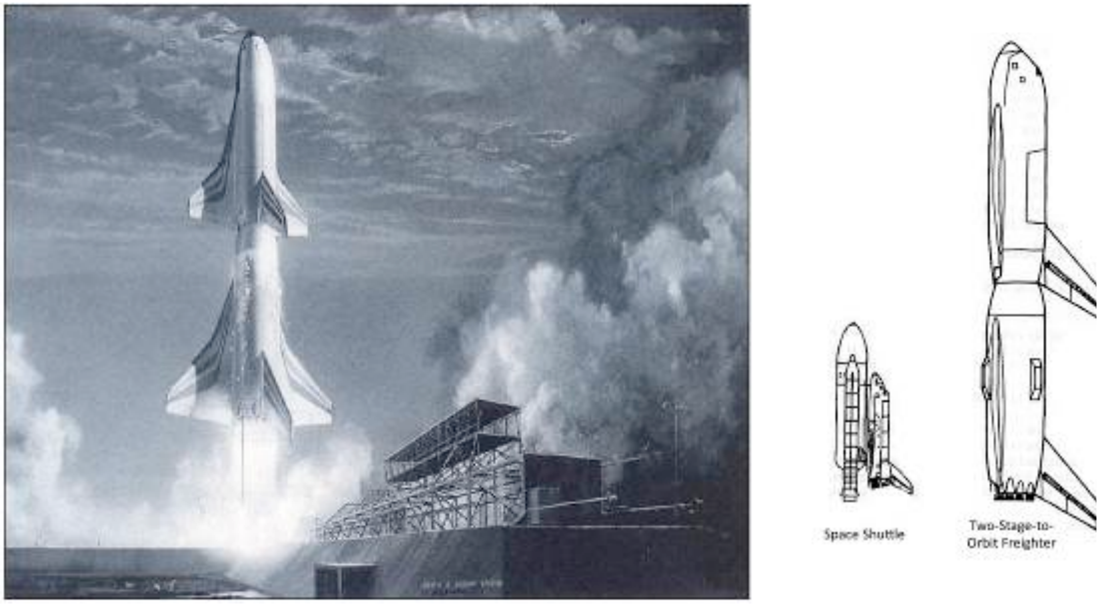
Union, Japan, Europe and others). Since the beginning of Space Shuttle operations in 1981, however, there have been seemingly endless changes in national policy, technology R&D, and systems development options as they relate to space launch. This issue must be resolved if low-cost access to space is to be achieved.

So, if the problem of ETO for SPS can be solved, why hasn't it? That story is a rather strange one, and spans much of the past 35 years.

The 1970s

During the late 1970s, SPS studies identified the need for large, fully-reusable two-stage to orbit (TSTO) launch vehicles to enable economically viable solar power from space. Figure 7-13 presents a conceptual illustration of one such concept, including a size comparison of this concept to the U.S. space shuttle, indicating the tremendous difference in scale between these space transportation system concepts.

Figure 7-13 1979 Reference System SPS TSTO ETO Transportation



Credit: NASA Art (c. 1979-1980)

This very large-scale TSTO approach was planned to launch payloads of more than 250 MT into LEO, with a GLOW (gross lift-off weight) estimated to be as high as 11,000 MT. The facilities required to support these enormous HLLVs were extremely large as well and would have involved extensive operations and maintenance. Nevertheless, the ETO cost per kilogram of payload for these launch systems was projected at an exceptionally – and almost certainly unrealistically – low figure: about $50-$100/kg (in 1979 US dollars). This is equivalent to a cost of about $200-$400 per launched kilogram (in 2013 US dollars). Based on the considerations we discussed above, a more credible estimate for the recurring payload cost per kilogram of a first generation, 99% reusable, two-stage-to-orbit (TSTO) vehicle would be about $2,000 per kilogram.

For in-space transportation, 1970s studies examined a range of options; one was that the SPS platforms would be partially constructed in LEO and would then "self transport" to GEO for final completion and operations. Solar electric propulsion was one technology option. Another was based on "WPT bootstrapping." This idea was proposed by William (Bill) Brown, whom we met in Chapter 3 as one of the inventors of microwave wireless power transmission (WPT). In

Brown's concept, known by the name "transportronics," after the first SPS was deployed, later systems would move from LEO to GEO via WPT electric propulsion (with the power delivered from GEO.

Selected Developments in the 1980s

1981 saw NASA begin Space Shuttle operations in the context of a US policy dictating that there would be a single "national space transportation system" (NSTS). However, following the Challenger accident (1986), American national policy moved sharply away from the NSTS approach and toward a long-term (perhaps permanent) commitment to a mixed fleet architecture to meet US space launch requirements.

During the 1980s and the early 1990s, many studies of future space launch systems were conducted. Several major technology programs were also initiated and billions of dollars invested. In fact, approximately every 12-18 months for over a decade, NASA, DOD, or Industry initiated yet another study of future space launch systems. (It should be no great surprise that progress has been so long in coming in the US.) A variety of programs were pursued in various other countries during the same timeframe, although far fewer than in the U.S. The following paragraphs briefly summarize a few of the major examples of these US and international activities and highlight some aspects of the evolution of ETO transportation planning to the present.

National Aerospace Plane. In the early 1980's, a major, jointly sponsored US Air Force (USAF)-NASA space access initiative was organized: the National Aerospace Plane (NASP) program. The goal of NASP was nothing less than an exceptionally aggressive technological leap-frog beyond the partially-reusable, rocket-powered Space Shuttle (with its LOX-Liquid Hydrogen Space Shuttle Main Engine) to a scramjet-powered, much more reusable, vehicle concept that was hoped to be capable of achieving single-stage-to-orbit (SSTO) operations. The basic vehicle concept for NASP was a highly aerodynamic vehicle which would make the transition to all-rocket flight at a very high speed (i.e., Mach 24+), and achieve a drastic reduction in the cost of access to space. NASP was at heart a research program, despite initial planning for a nominal flight test vehicle: the "X-30." Operational system definition represented a relatively minor aspect of the program and after the first several years, NASP settled on its now well-known configuration. While significant strides were made in technology, little effort was applied to the examination of alternative systems concepts. Ultimately, the joint NASA-USAF NASP effort was terminated in the first years of the 1990s.

Space Transportation Architecture Study. In 1985, the Reagan Administration directed NASA and the Department of Defense (DOD) through a "National Security Decision Directive" (NSDD) to jointly formulate a common plan for development of a second-generation space transportation system (beyond the Space Shuttle). The result was the Space Transportation Architecture Study (STAS). This effort was predominantly targeted on meeting government mission needs and assuring US leadership (in the context of the Cold War era). On the NASA side, mission drivers focused on large-scale Lunar-Mars programs. On the DOD side, mission drivers arose dominantly from the projected needs of the Strategic Defense Initiative Organization (SDIO). The STAS activity examined a wide range of system concepts and architectures – but these were consistently driven by government mission needs. STAS did not treat in any meaningful way the idea that drastic reductions in launch costs might lead to significant new commercial space markets. Among its conclusions, the study found that ELVs were not competitive for low-cost launch (a point that we discussed earlier), and supported continuing R&D for pretty much everything else (solid rocket motors, SSTO, air-breathing propulsion, etc.).

Advanced Manned Launch Systems. During the late 1980s, NASA and industry examined a variety of different vehicle concepts under the banner of Advanced Manned Launch Systems (AMLS) studies. This effort examined options that were both nearer-term and more "advanced" in terms of the level of technology incorporated, but which approached the problem of space launch from a very different direction than that of NASP. Following as it did the Challenger disaster, the focus of AMLS and related efforts was on the eventual replacement of the Space Shuttle, emphasizing evolution and higher levels of reusability, but not on driving technology to a revolutionary leap forward. These improvements were to be achieved either through a two-stage-to-orbit approach (nearer-term) or through an SSTO system (a more advanced option).

ALS and NLS. Consistent with the thinking that produced STAS but influenced by the Challenger accident, DOD and NASA pursued a number of expendable launch vehicle (ELV) ETO transportation technology development programs during the late 1980s and early 1990s. The Advanced Launch System (ALS) and its successor, the National Launch System (NLS), represented a major push in the post-Challenger accident era back toward ELVs that depended upon high flight rates and large payloads to achieve economical launch costs. A major aspect of the ALS/NLS concept was an emphasis on the need to develop a new high-performance but lower cost LOX-Hydrogen engine: the Space Transportation Main Engine (STME).

The focus of ALS/NLS efforts was on eventually launching new government missions (SDI and SEI-like exploration programs), emphasizing evolution of ELVs and driving technology even less than did earlier AMLS/Shuttle-II concepts (much less the leap-frog vision of NASP). The fundamental strategies embodied in these studies were: (1) that low cost could be achieved using ELVs, assuming the system procurement rates were high enough, and (2) system procurements could be driven up by high flight rates, common technologies, and by systems commonality between vehicles of various sizes (the core vehicle plus add-ons approach).

Space Exploration Initiative. In the midst of all of this, on July 20, 1989, then-President George H.W. Bush made a visionary speech on the steps of the Air & Space Museum in Washington, D.C., the Space Exploration Initiative (aka, "SEI", which was originally called the "Human Exploration Initiative") sprang onto the space launch scene. SEI brought with it a host of specialized ETO systems – primarily heavy lift launch vehicles (HLLVs), with strong heritage from the Space Shuttle – that were intended to launch first missions to the Moon and later to Mars. SEI assumed the existence of a robust infrastructure in low Earth orbit for basing, refueling, and repairing reusable in-space transportation systems. SEI's 90-Day Study (so-called because it was conducted during the ninety days following the speech by President Bush) was jostled by the Synthesis Group Report, commissioned by the White House-based National Space Council in the 1990 timeframe. And during the next year or two, NASA's Office of Exploration moved beyond in-space infrastructure to the First Lunar Outpost (FLO), which proposed a stupendously large HLLV (with a capacity of more than 250 MT payloads to LEO). With the inauguration of the then newly elected President William (Bill) Clinton in early 1993, SEI and all of its launch vehicle concepts were terminated.

Selected Developments in the 1990s

The US National Research Council (NRC) periodically took an interest in the problem of evaluating the many options available for ETO transport. For example, in 1991, the NRC's Aeronautics and Space Engineering Board (ASEB) was asked by the US House of Representatives to "assess the requirements, benefits, technological feasibility, and roles of earth-to-orbit transportation systems and options." The report that resulted from this effort, completed in 1992, was entitled "From Earth to Orbit – An Assessment of Transportation Options." In this review, the NRC basically embraced (a) the National Launch System (NLS), provided that the smallest, commercially oriented version of this essential expendable system be developed first; (b) the NASP program insofar as technology research was concerned; and (c) the DOD's SSTO technology program (but not 1/3-scale technology validation). In other words, the NRC took a position that all of these investments should be pursued – even though they were grounded in very different strategic visions of how ETO capabilities should be advanced.

The missions that drove this particular NRC assessment included the typical set: existing government and commercial launches and major new government missions, including (1) GEO telecommunications satellites on the commercial side, (2) Space Station and exploration for NASA, and (3) current spacecraft and eventually SDIO payloads for the DOD. The goal endorsed by the NRC was a one-third to one-half reduction in launch operations costs, targeted on the US maintaining its competitiveness in the international commercial launch vehicle market (for existing payloads) – but very modest compared to the visionary goals that had stimulated the original NASP program investment decision.

Also during the 1990s, several developments led to the emergence of a rash of new launch vehicle efforts (mostly reusable). The first was the successful development for the US DOD Defense Advanced Research Projects Agency (DARPA) by the MacDonald Douglas Corporation (which no longer exists) of the "Delta Clipper."

Delta-Clipper (later Clipper Graham). At the beginning of the 1990s, the DOD undertook technology R&D, targeting extremely low-cost ETO transport. The driving mission for these efforts was the Strategic Defense Initiative Organization (SDIO) and its projected need for large numbers of launches to deploy space-based missile defense systems. The result was the "Delta-Clipper" program, which produced a relatively low altitude fully reusable vertical take-off and vertical landing (VTVL) demonstration vehicle that used liquid oxygen (LOX) and liquid hydrogen (LH_2) as propellants. This project and vehicle (known by the mid-1990s as "Clipper Graham"[25]) was highly successful for several years. However, following NASA's adoption of the project, an accident in 1996 during landing resulted in a Hydrogen tank rupture and a fire that destroyed the vehicle.

Commercial Space Transportation Study. During the 1980s and early 1990s, the "market" foundation for the many space launch studies and technology programs that were undertaken had nothing to do with the commercial market. Instead, these efforts tended to be focused on meeting the space launch mission needs documented in the Civil Needs Data Base (CNDB). Meeting CNDB requirements led to an extended discussion regarding "assured access to space" – including several low technology approaches to Space Shuttle back-up systems. However, the real drivers for future systems came down to two: Strategic Defense Initiative (SDI) space-based systems deployment, and NASA Lunar-Mars launch requirements. Both of these demanded relatively high traffic per year in heavy lift launch vehicles – where forces outside the market, such as government specifications, dictated the payloads. As a consequence, the systems that resulted tended to be able to achieve low cost launch because they assumed high flight rates stimulated by government resources.

During 1993-1994, six major aerospace companies working with the NASA Langley Research Center conducted the Commercial Space Transportation Study (CSTS) that challenged the existing paradigm. The objective of this groundbreaking effort was to determine what the elasticity of potential future markets might be in terms of access to space cost reductions. The CSTS study examined ten (10) potential market sectors across a very wide range of possible launch prices – reaching all the way down to prices of less than $500 per payload-pound (or about $1,000 per kilogram). The types of new markets that were considered by CSTS included:

- Communications
- Space Manufacturing
- Remote Sensing
- Government Missions
- New transportation service sectors (including space tourism and hazardous waste disposal in space)
- Entertainment
- New Missions (including a space business park)
- Space Utilities (in particular, generation of power for transmission to Earth)
- Commercial utilization of extraterrestrial Resources
- Commercial advertising

The fundamental result of the CSTS study was the opportunity to make a fundamental change in US space launch strategic thinking. CSTS found that if launch prices could be driven low enough – below about $500 per payload-pound (in early 1990s dollars), then radical increases in space launch traffic could be expected. Here, then, was a foundation for large ETO traffic without resorting to major new government programs (such as the Strategic Defense Initiative, SDI, or the Space Exploration Initiative, SEI). In my view, CSTS established the foundation for the reusable launch vehicle R&D programs – such as X-33 – that emerged later in the 1990s.

Access to Space Study. In response to a Congressional request in the NASA FY 1993 Appropriations legislation, NASA's Access to Space Study (1993-1994) examined a focused set of options for future launch systems with an eye on what should be the next NASA focus for space access – ranging from upgrades of the Space Shuttle to new, low-risk technology systems (typical of the "assured access to space" variety), to possible advanced technology replacements for the Space Shuttle early in the new Century. This study had many similarities to earlier AMLS and Shuttle-II efforts, but was a conscious departure in its effort to examine several different levels of technical risk and potential payoff. Multiple concepts in three options were examined: Option 1, low risk (Shuttle evolution); Option 2, moderate risk (several new systems, but making only modest changes in technology); and, Option 3, high risk (with three very new systems).

As we discussed previously, in the same time frame DARPA initiated a single-stage-to-orbit technology validation project – the origin of what became known as the "Delta Clipper." Ultimately, one of the system concepts from the Access to Space study's "Option 3" was recommended: an all-rocket, single-stage-to-orbit (SSTO) vehicle with the projected potential to drive launch costs/prices down into the range of $1,000 to $2,000 per payload pound (i.e., roughly $2,000-$4,000 per kilogram). The market focus of the study remained the basic government and commercial missions documented in the CNDB. Still, a new era in space launch planning and development has been established on this foundation.

A New Start for Low-Cost ETO: RLV. The Reusable Launch Vehicle (RLV) program initiated in the 1994 time frame was founded on the results of earlier DOD SSTO technology developments and the Access to Space Study. It was grounded in US National Space Policy, which directed NASA to undertake reusable launch research for a mid-term new vehicle. At the same time, the US DOD was assigned responsibility to develop a nearer-term operational system: the Evolved ELV (EELV) program. The resulting NASA program focused dominantly on prospects for a near-term, all-rocket solution to the challenge of a very low cost space launch.

The RLV program comprised several major demonstration efforts – including the X-34 (sub-scale, air-launched system) and the X-33 (partial-scale, sub-orbital system).

Through the RLV program, the first significant investments in a major, new, reusable ETO system since NASP were started. The program made critically needed investments in diverse technologies – including materials, propulsion, structures avionics and others. The first phase of the program addressed three major vehicle concept options (all LOX-Hydrogen SSTO approaches): a vertical takeoff, vertical landing (VTVL) system, a vertical takeoff, horizontal landing (VTHL) winged body concept, and a lifting body VTHL approach. Ultimately, the VTHL lifting body approach, proposed by the Lockheed Martin Corporation won the competition and went forward as the X-33 demonstration vehicle.

A fundamental element of the RLV program strategy was that government should and must play the role of "enabler" for advances in capability – conducting research and developing technology – but that industry should lead in the development of new reusable launch systems (including funding). It was expected that the RLV program's X-33 demonstration would establish the technological foundation for ETO transportation at costs of less than $1000 per payload pound. The RLV program represented a significant change in US launch planning and technology development. It was founded on a new type of relationship between government and industry, and didn't rely on the implementation of new, large-scale government initiatives (for example, SDI and SEI) for its rationale. However, it was very challenging programmatically, and ultimately unsuccessful. Market forces and industry decisions did not support the RLV strategy in the long run; the planned X-33 demonstration did not occur, and there was no commercial vehicle (the "Venture Star").

In parallel during the latter 1990s, in order to ensure that access to space was uninterrupted, NASA continued to make needed, safety-related upgrades to the Space Shuttle system and conduct studies of possible capability-related upgrades that would enable the Shuttle to provide effective service beyond its projected phase-out date (circa 2013-2015) in the event that commercial RLV's were developed in that time frame. (Of course, in 2003, the loss of Space Shuttle Columbia drove the Bush White House to order early termination of the Space Shuttle Program.)

RLV in the 90s included an advanced technology component – the Advanced Space Transportation (AST) Program – and represented not just a particular project (e.g., X-33) but more generally a potential series of experiments and demonstrations and a foundation of supporting research and technology development. With regard to ETO, the established goal of this element of the RLV program was to enable a dramatic step below $1000 per pound to LEO. To guide these investments, advanced vehicle concept studies were conducted.

Commercial Developments. The 1990s also saw various ambitious (perhaps overly so) developments in the commercial marketplace that stirred the pot even further. Companies pursued a range of large-scale LEO based constellations of space communications satellites. Some of these were eventually deployed (e.g., Iridium) and others were not (e.g., Teledesic), but while there were in development, they – along with continuing DOD requirements – inspired considerable interest in low cost launch. Various companies sprang up, such as *Kistler*, *Rocketplane*, *Rotary Rocket*, and others – each with a different approach to the RLV concept. This part of the story merits several pages by itself; however, in the interests of brevity, suffice it to say that none of these efforts resulted in a flight vehicle.

Highly Reusable Space Transportation. During 1995-1997, the farther term was also being examined. NASA's Highly Reusable Space Transportation (HRST) study examined a wide range of options for dramatic reductions in space access costs that might be achieved in the mid- to far-term. This study was focused on the question: how might payloads in the 10,000-20,000 kg class be launched to LEO for costs as low as $200/kg? The types of payloads that comprised the launch requirements for the HRST study included bulk materials (e.g., propellants), fragile space systems (e.g., conventional spacecraft, SPS or other platform system elements), and astronauts. Figure 7-5 presents a conceptual illustration of one of the more interesting systems concepts (which employed launch assist) that emerged from NASA's HRST study – the Argus-MagLifter combination.

Figure 7-16 Launch-Assisted SSTO ETO Transport Concept

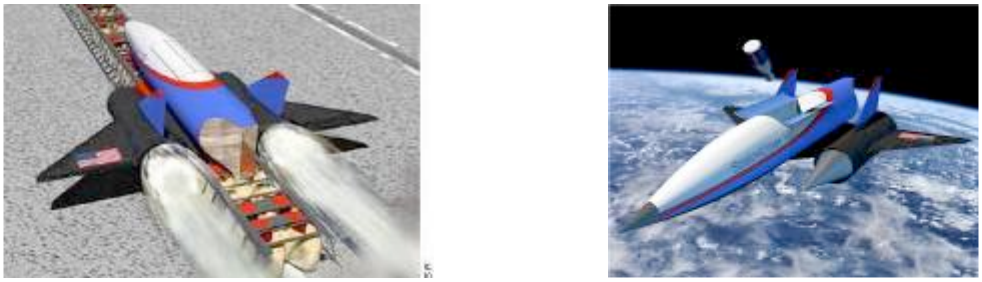
Credit: NASA Art, by P. Rawlings / SAIC c. 1996

The fundamental findings of the three-year HRST study were the following: (1) expendable launch vehicles will not be able to accomplish exceptionally low cost launch costs; (2) in order to realize very low cost/kg to be launched, reusable launch vehicles must be highly reusable (in other words, they must be able to achieve more than 1,000 flights per airframe); and (3) a key driver of low maintenance and high reusability is a factor described as "operational margin" for key systems, such as propulsion.

Various systems options and vehicle technologies were highlighted by the HRST study. Some of the most promising items included advanced materials for cryogenic engines that might enable higher thrust-to-weight (T/W) than that of existing engines; novel engine cycles, such as rocket based combined cycle (RBCC); and new materials for vehicle structures and thermal protection systems (TPS). Another was the concept of "launch assist" in which some portion of the total energy needed to reach orbit is provided off-board from the primary vehicle (e.g., in the form of a catapult concept or air launch); this was found to be particularly promising.

Coincidentally, shortly after the conclusion of the HRST advanced concepts study, the RLV program was in jeopardy due to technical and programmatic issues with the X-33 project. In the somewhat frantic and certainly hurried efforts (c. 1998-1999) to develop an alternative to present to the US Congress, I had the opportunity to brief the planning team on the results of HRST study. The upshot was the brief existence of the "SpaceLiner100" program, the goal of which was to develop a system that might achieve launch costs of $100 per pound ($200 per kilogram) to LEO. Figure 7-17 presents several views of the baseline concept – which shows a clear heritage to the Argus-MagLifter concept developed by HRST.[26]

Figure 7-17 SpaceLiner 100 Conceptual Illustrations



Credit: NASA Artwork c. 1999

From my perspective, it was unfortunate that this program concept was almost immediately folded into the Space Launch Initiative (SLI), described later. The ambitious goal of truly low cost launch was relegated in that program to the category of "3rd generation RLV" and the distant future, while program funds were focused on a nearer-term, multi-stage reusable launch vehicle.

Developments in Europe: FESTIP. During the mid-1990s, the European Space Agency undertook a program that paralleled RLV activities in the US: FESTIP (Future European Space Transportation Investigations Program). In this program, promising RLV concepts were studied, respective technology needs identified, and associated technology development and verification plans defined.[27] Beginning in 1994 and ending in 1998, the emphasis in FESTIP was in general on the rocket equation (discussed earlier), and in particular on how the mass ratio (mass final divided by mass initial) might be improved. Unfortunately, this program to reduce the cost of access to space for European missions did not go forward.

In the 1996 timeframe, an Ariane-V launch failed catastrophically; this drew attention away from possible investments in the future to the challenges of launch with ELVs. Moreover, it was reported at the time that within ESA, FESTIP was being funded by Germany only, and that other key players – particularly France – were not involved in the preparatory program but they were committed to the Ariane ELV program.[28] Within the next two years (1997-1998), critical issues arose in the fabrication of the liquid Hydrogen (LH_2) tank for the NASA X-33 single-stage-to-orbit RLV demonstrator. With the emergence of serious issues in the US program and lack of commitment to a European RLV program, FESTIP was terminated by 1998 and the goal of low-cost launch deferred for Europe.

Deep Space One.[29] An important development for SSP in-space transportation came from an unexpected quarter: the success of NASA's Deep Space One (DS1) Mission. Launched in 1998, this project was pursued under the New Millennium Program (the goal of which was the validation of new technologies for future science missions). DS1's ion thrusters on the spacecraft operated successfully from 1998 until 2001, establishing long-lived, solar electric propulsion as a viable technology. DS1 also demonstrated various other relevant technologies, including new approaches to increasing spacecraft autonomy (a key capability for SSP) and multiple bandgap, concentrating solar PV arrays for high-efficiency power.

Selected Developments Since 2000

The Space Launch Initiative and the Integrated Space Transportation Plan. After the RLV program and the HRST advanced concepts study, NASA moved on to a somewhat modified ETO technology effort under the framework of the Integrated Space Transportation Plan (ISTP). One NASA effort within the framework of the ISTP was the Orbital Space Plane (OSP), which proposed to develop a small capsule or lifting body type vehicle that would be lofted into orbit by an Expendable Launch Vehicle. This program would have replaced the crew launch capacity of the US Space Shuttle with a smaller, stand-alone crew carrier. The other was the Next Generation Launch Technology (NGLT) program. NGLT was an R&D effort focused on a reusable cargo-to-orbit system for the US. This program initially envisioned developing a three-stage-to-orbit unpiloted cargo vehicle.

The Vision for Space Exploration. Ultimately, another Space Shuttle accident – this time the catastrophic failure during reentry of the Space Shuttle Columbia's thermal protection system (TPS) on February 1, 2003 – transformed yet again US efforts vis-à-vis access to space. Over the course of the next year, and in rather successful secrecy – particularly for Washington, D.C. –

a new space policy was formulated which became known when announced by then-President George W. Bush as the Vision for Space Exploration (VSE). Unfortunately for the goal of low cost launch and reusable launch vehicles, with the announcement of the VSE, NGLT had been integrated programmatically into the budget of the Exploration Systems Mission Directorate (ESMD). A series of reviews made it clear that the ISTP in general and NGLT in particular were not developing launch capabilities required to establish an outpost on the Moon.[30] In 2004, the program was slated for fundamental restructuring. A useful and ultimately important outcome of these discussions (and the VSE) was to establish a goal of using commercial companies to provide access to low Earth orbit and to the International Space Station. These were the beginnings of the current US commercial cargo and crew launch programs.

At any event, by the latter months of 2005 to early 2006, then-NASA Administrator Michael Griffin refocused the VSE on a specific set of system choices that closely resembled (as he characterized it at one point "Apollo on Steroids." A part of that effort was the final elimination of the goal of low cost launch, and the focus of NASA ETO technology efforts on new, Shuttle-derived human exploration focused launchers – the Ares I crew launcher, based on the Solid Rocket Booster (SRB) and the Ares V heavy lift vehicle, planned to be bigger than the Saturn V of the 1960s.

FLPP (Future Launcher Preparatory Program). Shortly after 2000, the European Space Agency undertook a follow-on study to FESTIP: FLPP (Future Launcher Preparatory Program).[31] This effort – involving both studies and technology R&D – ran from 2006 to 2012, and targeted the deployment of a next generation post-Ariane V launch system by the 2025 timeframe. As of this writing, it remains to be seen how, or whether, ESA will pursue these goals in the coming years.

Current Events

During the past 10 years, there have been several developments that are highly relevant to solving the space transportation needs of SSP. These include developments not by government laboratories, nor by traditional major aerospace contractors, but rather by newcomers.

Space Exploration Technologies. In the US, the relatively new firm "SpaceX" (Space Exploration Technologies), founded by Elon Musk, has advanced a remarkable suite of modular, evolvable low-cost launchers. The "Falcon 9" launcher, for example In fact, as of 2012, the posted price for the operational Falcon 9 ELV provided by SpaceX was $54M for a payload up to 10,454 kg, i.e., a rate of some $5,165 per kg. Even this relatively low cost is slated to be reduced with a planned upgrade of the Falcon 9 to increase its payload, but not the cost, by 25% – resulting in a rate of no more than $4,109 per kg ($1,870 per pound).[32] In addition, SpaceX has for the past several years been pursuing a strategy of incorporating reusability into its existing fleet of expendable vehicles. During 2012-2013, they have undertaken a series of take-off and landing tests of a restartable version of the Falcon launcher, under the moniker "Grasshopper." These tests are purportedly targeted on a reusable first stage for a future version of the launcher, which is already low cost.

Reaction Engines Ltd. In the United Kingdom (UK), there have been interesting developments in the field of SSTO to LEO during the past 20-plus years. These have centered on the efforts of a single firm, Reaction Engines, Limited, a particular vehicle, Skylon (derived from the former HOTOL concept), and a specific technology, the SABRE (Synergetic Air-Breathing Rocket Engine) propulsion system (incorporating both jet turbine and rocket elements).[33] In the past several years, Reaction Engines, Ltd. has made good progress both technically and programmatically. For example, receiving good marks from an ESA review of the technology in November 2012, and winning on 17 July 2013 some £60 million (equivalent to roughly $90 million) from the government of the United Kingdom which will reportedly be matched by private investors. If development proceeds successfully, the SABRE engine will ready for testing circa 2020. The company's planned SKYLON RLV would have a capacity to place approximately 15,000 kg in low Earth orbit, at an initial projected cost of approximately $1,000 per kilogram.

XCOR.[34] Yet another small firm, XCOR has pursued a completely different approach to advanced, low cost chemical and cryogenic propulsion: a piston-driven rocket. Targeted on the sub-orbital space flight market and their vehicle, "Lynx", the XCOR rocket engine has the potential for applications in a wider variety of systems, including lower cost in-space propulsion. Reportedly, XCOR has plans to extend its initial sub-orbital Lynx vehicle to a fully reusable, two-stage-to-orbit (TSTO) vehicle, capable of delivering small payloads to LEO at very low cost.

USAF X-37.[35] Also in the past decade or so, the USAF has deployed a new, miniature "space shuttle like" vehicle: the X-37, which operates as a reusable upper stage to provide rapid access, with high maneuverability for payloads to LEO. The vehicle designated "X-37" began in 1999 as a NASA technology demonstration program; it was later transferred to the Air Force and was developed by the Boeing Company. It has flown three times: 2006 (a drop test), 2010 (LEO, for 8 months), and 2012 (LEO for 6 months). The X-37 has been launched on an Atlas V rocket.

DARPA XS-1 Program. In September 2013, the DARPA Tactical Technology Office (TTO) announced that it would be undertaking a new reusable launch vehicle program: XS-1 (Experimental Spaceplane-1), the goal of which will be to develop a reusable demonstration vehicle that can accomplish a suborbital flight 10 times in 10 days. The objective is for the XS-1 to carry an expendable upper stage capable of placing payloads weighing up to 1,800 kilograms into orbit at a target price of $5 million per launch (or about $2,800 per kilogram).[36]

In-Space Transportation: Hall Effect Thruster R&D.[37] Beginning in the 1960s and continuing to the present, a particular type of electric propulsion – known as a "Hall Effect" Thruster – has been under development by a wide variety of countries and companies. (Early leaders in this technology were researchers in the former Soviet Union.) Progress in this technology, which has good fuel efficiency and the potential for higher thrust than ion thrusters, has been particularly strong since 2000. For example, in 2003, the European Space Agency was the first to use Hall Thrusters on the SMART-1 lunar mission. In the US, various thrusters have been developed, including the highest power Hall Thruster that has flown as of the date of this writing: the Aerojet BPT-4000, launched to GEO in August 2010 on the military Advanced Extremely High Frequency (AEHF) communications satellite. The BPT-4000, which operated at 4.5 kW, provided orbit raising as well as station keeping in GEO.

In-Space Transportation: NASA SEP R&D.[38] Finally, during 2013, NASA has proposed a major new research and development effort targeting solar electric propulsion (SEP). This effort, which is under the auspices of NASA's new asteroid / small bodies initiative, will significantly advance current capabilities by developing and demonstrating a 40 kilowatt propulsion system.

So, What Does All that Mean for Space Solar Power?

Strategically then, in the US and to a lesser extent internationally, government-sponsored R&D and systems development for Earth-to-orbit transportation has for more than 30 years suffered from a form of "bipolar disorder," alternating two or three times each decade between the goals of low-cost access to space for a variety of mission applications (including commercial space), and heavy lift focused on government space missions in general and human exploration in particular. Often, when low cost and commercial space have been the goals, a reusable transportation solution has been pursued. And, when human exploration requirements have been at the forefront, expendable heavy lift vehicles have been preeminent. Table 7-5 summarizes many major space transportation efforts of the past 30 years.

As shown in this partial listing, every few years the goals and objectives of space launch development have shifted, and programs of the time completed, not pursued, or cancelled outright. In my view, this strategic planning disorder has consumed billions of dollars, decades of time, and the careers of many good aerospace engineers.

In the 1970s, it was argued that the US Space Shuttle would revolutionize access to space – launching as frequently as weekly and at very low cost. Notwithstanding, SPS systems studies of the day looked beyond the Space Shuttle to larger payloads and lower costs and requirements for new, much larger vehicles. However, those studies were cancelled, and the Shuttle never achieved high launch rates or low costs. All that remained in the early 1980s were international efforts, far-term advanced technology research (e.g., the NASP program), and high-level planning for the eventual evolution of the Space Shuttle. Then, in 1986, the Challenger disaster changed everything and set into motion the ETO space transportation technology and system development efforts of the next generation or two.

Earth-to-orbit Solutions

Naturally enough, in the immediate future (i.e., the next 5-10 years), only currently operating ELVs or those vehicles already in development will be available for use. For many years, the standard view of ETO transport costs has been that they would – almost like a physical law – remain in the range of $20,000 to $40,000 per kilogram with the prior number reflecting the cost performance of a typical expendable launch vehicle (ELV), and the latter value being the cost for launch using the Space Shuttle (retired in 2011).[39] More than any other issue, these extremely high historical costs have been cited as a reason why SPS could not be realized. However, during the past five years, this common wisdom has been overturned by lower cost ELV service provides such as Space Exploration

Technologies, Inc. (aka, "SpaceX"). As we saw earlier, such firms are now offering launch services at prices well below $10,000 per kilogram to LEO.

Fortunately, through the next decade all of the objectives that must be achieved to realize SSP can be accomplished with ELVs – albeit with rather large numbers of launchers! There are also several possible new launch capabilities that could become available in addition to existing services.

As was mentioned previously, a number of technology and systems level demonstrations can be accomplished without new space transportation. Early SPS projects such as an initial pilot plant in GEO or systems designed to serve so-called premium niche markets could be most cost-effectively launched using a mass-produced expendable launch vehicle. There are several low-cost ELV projects underway that might well serve this application. This strategy of early ELV use has the potential to eliminate a flaw in previous SPS strategies in which large initial investments in new launch systems (and other infrastructure) were essential to any progress.

Several mid-term reusable launch vehicle system concepts appear to be capable of ETO transport to LEO at specific costs of about $500 to $1,000 per kilogram, depending on the launch rates achieved. Such options were examined in the 1990s HRST study. Not surprisingly, this is an area that requires far greater study than was possible by either the 2008-2011 IAA study or the 2011-2012 NIAC effort.

In-Space Transportation Solutions

Current systems for in-space transport from LEO to GEO (geostationary Earth orbit) or from a GEO transfer orbit (GTO) to GEO are represented by simple, expendable upper stages. Frankly, these systems are entirely insufficient for even the smallest SPS technology demonstrations in GEO. However, a range of more advanced technology options have been under development for many years and could readily make reusable in-space vehicles achievable in the coming decade.

The principal propulsion options are cryogenic chemical propulsion and solar electric propulsion. For in-space transportation systems such as would typically be used to move SPS elements from LEO to GEO, a key issue is that the high-thrust systems that could provide fast round-trip times are comparatively low in fuel efficiency (e.g., with Isp of 250-460 seconds), while the systems that provide high fuel efficiencies (e.g., Isp of 1,500-3,000 seconds or more) are low-thrust and are not capable of achieving fast trip times.

These issues must be examined in future studies; however, it appears that the best solution may well be a reusable SEP OTV.

Table 7-5a Synopsis of Relevant Space Transportation Efforts since 1980

Program	Era	Country	Program Objectives
National Aerospace Plane (NASP)	1980s	USA	Technology Research
Shuttle-II and Adv. Manned Launch System (AMLS)	1980s	USA	Systems Studies
Energyia - Buran	1980s	USSR	System Development
Advanced Launch System (ALS) – a.k.a., NLS (National Launch System)	1980s	USA	Systems Studies and R&D
STAS (Space Transportation Architecture Study)	1980s	USA	Systems Studies
Shuttle-Cargo (“Shuttle-C”)	80s-90s	USA	Systems Studies
Space Exploration Initiative (SEI) First Architecture - ETO	1989-1991	USA	Systems Studies and R&D
Space Exploration Initiative (SEI) First Architecture - In-Space	1989-1991	USA	Systems Studies and R&D
Commercial Space Transportation Study	Early 1990s	USA	Market Analysis
Access to Space Study	Early 1990s	USA	Systems Studies
Delta-Clipper	Early 1990s	USA	Technology Demonstrator
RLV (including X-33, X-34)	1990s	USA	Systems Studies and R&D
Highly Reusable Space Transportation	1995-1997	USA	Advanced Concepts Study
ESA FESTIP	1994-1998	ESA	Systems Studies and R&D
Deep Space One	1998-2001	USA	Technology Demo Mission
Next Generation Space Transportation	2002-2005	USA	Systems Studies and R&D
Ares-I	2005-2009	USA	System Development
Ares –V (HLLV)	2005-2009	USA	System Development
ESA FLPP	2004-2012	ESA	Systems Studies and R&D

Program	Era	Country	Program Objectives
Orion Capsule	2005-2013	USA	System Development
SLS (Space Launch System)	2009-2013	USA	System Development
COTS (Commercial Space Transportn.)	2005-2013	USA	System & Operations
X-37 (ELV-launched, reusable orbiter)	2005-2013	USA	System & Operations
SABRE Engine (for SKYLON)	To 2013	UK	Systems Studies and R&D
NASA Asteroid SEP Program	2013-on	USA	Systems Studies and R&D

Table 7-5b Synopsis of Relevant Space Transportation Efforts since 1980

Program	Vehicle Type	Mission /Objective	Status
National Aerospace Plane (NASP)	**Reusable**	Low-Cost Launch	**Cancelled**
Shuttle-II and Adv. Manned Launch System (AMLS)	**Reusable**	Space Shuttle Replacement	**Cancelled**
Energyia - Buran	**Mixed**	Space Shuttle / HLLV	**Cancelled**
Advanced Launch System (ALS) – a.k.a., NLS (National Launch System)	**Expendable**	Evolutionary Improvements in Launch	**Cancelled**
STAS (Space Transportation Architecture Study)	**Mixed**	Evolutionary Improvements in Launch	Completed/NFO*
Shuttle-Cargo ("Shuttle-C")	**Expendable**	Heavy Lift Launch	**Cancelled**
Space Exploration Initiative (SEI) First Architecture - ETO	**Expendable** HLLV	Human Exploration	**Cancelled**
Space Exploration Initiative (SEI) First Architecture - In-Space	**Reusable** LEO-Based	Human Exploration	**Cancelled**
Commercial Space Transportation Study	**Reusable**	Low-Cost Launch	Completed
Access to Space Study	**Mixed**	Low-Cost Launch	Completed
Delta-Clipper	**Reusable**	Low-Cost Launch	**Cancelled**
RLV (including X-33, X-34)	**Mixed**	Low-Cost Launch	**Cancelled**
Highly Reusable Space Transportation	**Reusable**	Low-Cost Launch	Completed/NFO
ESA FESTIP	**Reusable**	Low-Cost Launch	Completed/NFO
Deep Space One	**Spacecraft**	Tech Demo (SEP)	Completed
Next Generation Space Transportation	**Reusable**	Low-Cost Launch	**Cancelled**
Ares-I (Access to LEO)	**Expendable**	Human Exploration	**Cancelled**
Ares –V (HLLV)	**Expendable**	Human Exploration	**Restructured**

Program	Vehicle Type	Mission /Objective	Status
ESA FLPP	**Reusable**	Low-Cost Launch	Completed/TBD
Orion Capsule	**Expendable**	Human Exploration	Ongoing R&D
SLS (Space Launch System; HLLV)	**Expendable**	Human Exploration	Ongoing R&D
COTS (Commercial Space Transportn.)	**Expendable**	Access to ISS	Operational
X-37 (ELV-launched, reusable orbiter)	**Reusable**	Access to LEO	Operational
SABRE Engine (for SKYLON)	**Reusable**	Access to LEO	Ongoing R&D
NASA Asteroid SEP Program	**Reusable**	Deep Space Transport	Ongoing R&D

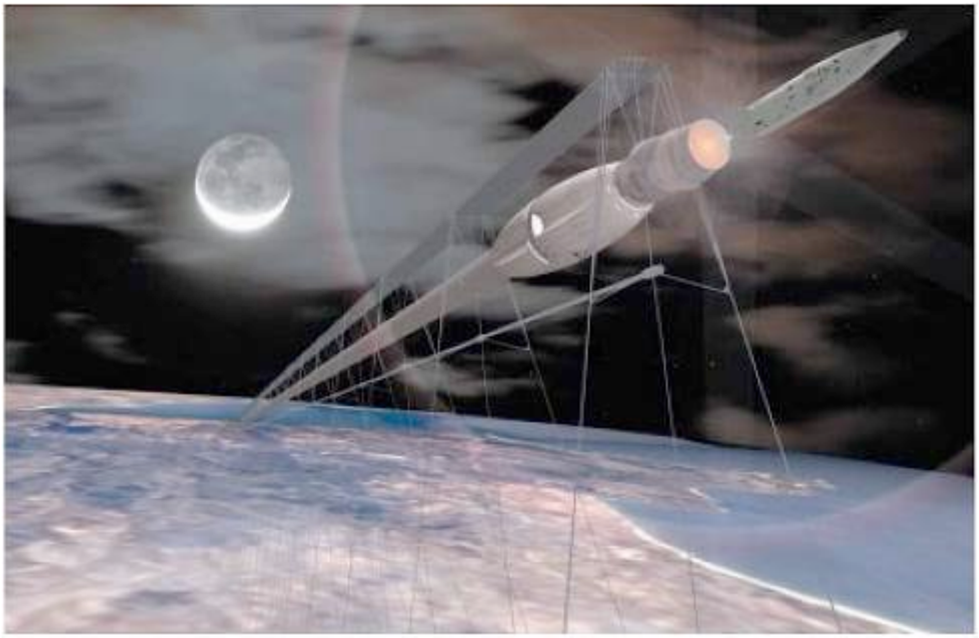
** NFO: No immediate follow-on*

In the farther term, advanced concepts using various advanced technologies such as rotating space tethers appear promising for in-space transportation. In addition, effective integration with ETO launch systems in the far term will be an important requirement for new in-space transports. For example, a sub-orbital vehicle might be integrated with a "sky-hook" tether. Such farther-term space transportation concepts are discussed in the section that follows.

The Far-Term: More Visionary Systems

There are several infrastructure-intensive space transportation systems options that are typically cited as options in the very far term. More often than not, these system concepts represent a novel integration of the functional requirements of launch to LEO and transportation from LEO to GEO. One interesting concept for the farther term is the idea of electromagnetic (EM) launch directly to Earth orbit. In the past two decades or so, Dr. James R. Powell has developed a unique concept that would employ an entirely ground-based approach using superconducting magnetic levitation (Maglev). This concept, called "StarTram," is illustrated in Figure 7-17.[40]

Figure 7-17 The Direct-to-Orbit EM Launch Concept: StarTram



Credit: Art Courtesy Dr. James R. Powell

In the case of the StarTram concept, a long low-acceleration maglev system accelerates a vehicle (with payload) to be launched to orbital velocities inside an evacuated tube. This tube is initially underground (during the acceleration portion of the track, which is the most massive), and then reaches up – eventually to some 20 km above the ground – via a superconducting magnetic levitation system.

Another such option is the idea of the "Space Elevator," in which an extremely huge structure – extending from the Earth's surface to GEO and far beyond – that would literally enable elevator-type cars to travel from Earth to space. This very challenging concept depends upon assembling a structure of about 70,000 km in length that is capable of enduring for decades the intense radiation environment of the Van Allen belts and maneuvering to evade orbiting spacecraft and large debris. Other, more tractable, options include various interim concepts, such as rotating tethers to create a "skyhook" approach, and farther term alternatives, such as the "launch loop." A rather different class of ETO advanced concepts involves ground-to-vehicle beamed power (e.g. with high intensity lasers) does not appear to be promising for SPS applications. This assessment is due in large measure to the quite modest payloads (i.e., below 100-1,000 kg) that are likely to be enabled by such systems and are not generally useful for SPS launch. Moreover, high power laser launch systems may also be readily weaponized; a concern we discussed at length in Chapter 4 in the context of an SPS that might employ laser wireless power transmission.

Some of these concepts hold out the promise of launch to space for extremely low marginal costs – about equal to the cost of the electricity required. However, it is my judgment that considerably more technology R&D is needed to establish the technical feasibility of the known far-term launch concepts, or to identify other, as yet-to-be-invented approaches.

An important point is that these highly ambitious systems approaches are not necessary to realize economically feasible Solar Power Satellites. Reusable launch vehicles (RLVs) in the mid-term will likely be capable of getting transportation costs down to below $1,000 per kilogram, and probably down to $500 per kilogram at high launch rates, which is all that SPS requires during initial deployments.

Closing Observations

In 1976, Dr. Peter Glaser testified before the US Congress on the topic of SPS – before the major studies of Solar Power Satellites in the US had started – and noted in his written statement:

> "The achievement of low-cost space transportation will be essential to the commercial success of the SPS."[41]

This remains no less true today. However, the required "specific cost" for SPS ETO services depends very much on the price point for the energy to be delivered and the market involved. There are also significant potential synergisms involved among future launch markets, as was observed by the NASA-industry Commercial Space Transportation Study (CSTS). It appears that the prospects are good for future capabilities that could achieve ETO costs as low as $500 per kilogram with high launch rates. Additional R&D is needed to establish which approach is most promising. However, during the coming decade, costs of access to space will remain considerably higher.

Low-cost space transportation is a classic "chicken and egg" conundrum: without a substantial existing market, how could a major investment – potentially involving tens of billions of dollars – be justified? Conversely, if low-cost launch systems don't already exist, then how can a new industry (such as SPS) that requires this capability win the necessary investment – again possibly involving tens of billions of dollars? (In the classic sense: no eggs, then no chickens; no chickens, then no eggs. Obviously, omelets are impossible!)

A very nice example of how this problem might be solved may be found in the history of one of the most famous (and beautiful) infrastructure projects of the early 20th Century: the Golden Gate Bridge in San Francisco, California. During the decades before the bridge was opened for traffic, ferries operated frequently between the city and Marin County on the far side of the Golden Gate (the gap at the entrance to the bay). The total traffic across the gap (people, vehicles and freight) was well known; opponents to the bridge argued that a new bridge would not only spoil a beautiful view, but would never pay for itself. Opponents discounted heavily the counter argument that there would be new, induced traffic. Fortunately, in the case of San Francisco the people stepped in: a local election resulted in a three-to-one victory for the issuance of a bond issue for funding of the new bridge. (It was the President of the then recently formed Bank of America who authorized the bank to purchase those bonds when, in the depths of the Great Depression, they failed to sell robustly.) The bond issue was a great success, and the bridge became the symbol of the city and the Golden Gate; tolls for vehicles crossing the bridge paid the debt in full.

The same might well prove true for the low-cost space transportation needed for Space Solar Power. As the CSTS study found, when the cost of launch falls below $1,000-to-2,000 per kilogram, new industries such as SSP will emerge and traffic will rise, and costs will drop still further. But, how can we get there from where we are today?

Some advocate for an immediate, enormous investment in infrastructure ($50 B to $100 B or more) as a prerequisite to Space Solar Power. However, an Apollo Program-class investment of this sort would require a complete change in the attitude of multiple governments toward SSP; in my view, this is totally unrealistic and unnecessary. The strategy proposed here is quite different, and enabled by the hyper-modular architecture embodied by SPS-ALPHA. Government-industry investments in enabling technology – such as that being undertaken by the UK and Reaction Engines, ltd. – are certainly needed. However, *at this moment* a massive investment of government funds in new space transportation systems is not needed.

The topic of in-space transportation has been examined very, very broadly by diverse studies during the past five decades. The cursory evaluation of the issue by the IAA SSP study (2008-2011) found that there are good prospects for significant reductions in the costs of Earth-to-orbit and in-space transportation during the coming two decades. This finding is in full agreement with the discussion presented in this Chapter.

In summary: expendable launchers are sufficient for SSP activities during the coming decade. Once SPS systems (and economics) are validated through large-scale demonstrations such as an SPS pilot plant in GEO, funding of RLVs – and dramatic reductions in the cost of space access – should become possible through relatively low-cost financing (as in the case of the Golden Gate Bridge some eighty years ago). Affordable in-space transportation will be needed sooner, particularly if an SPS pilot plant is to be deployed beyond LEO. For the near- to mid- term, reusable vehicles with high-efficiency solar electric propulsion (SEP) are the most promising approach to needed reductions in the cost of in-space transportation.

In the chapter that follows, we will turn next to the advanced in-space operations that must be developed in order to realize Space Solar Power.

[7-1] The propulsion used on the SPS platform is also important; however, this is not the topic of the current Chapter. On-board propulsion for SPS-ALPHA is discussed briefly in Chapter 5.

[7-2] It really *is* rocket science…! I must take a moment to note that this is *not* a book about space transportation or rocket propulsion; these are vast topics in their own right. Rocket propulsion is a topic that many aerospace engineers find compelling, and I must agree that watching a rocket launch in person is thrilling. My objective in this Chapter, however, is to indulge in just enough detail to persuade you, the reader, that the challenge of space transportation for Space Solar Power *can* be solved.

[7-3] The use of "g" (the acceleration of gravity on Earth) is due to the expression of propellant in terms of its weight on Earth, rather than its mass; both are common. In the case that mass is used, then Isp is expressed in units of "meters per second"; alternatively, if the weight is used, then Isp is expressed in units of seconds. The latter units are used in this report.

[7-4] See for example, the following website: http://en.wikipedia.org/wiki/Delta-v_budget

[7-5] The use of "g" (the acceleration of gravity on Earth) is due to the expression of propellant in terms of its weight on Earth, rather than its mass. In the case that mass is used, then Isp is expressed in units of "meters per second;" alternatively, if the weight on Earth is used, then Isp is expressed in units of seconds. The latter units are used in this book.

[7-6] For typical SPS in-space transportation concepts, neither aerobraking (A/B) or aeroentry (A/E) are used in combination with high-efficiency and low-thrust options, such as solar electric propulsion. As a result, A/B is not usually consider for SPS transportation. I will follow this custom here. However, I believe that future studies should look once more at this technology for possible application to SPS servicing – which is one reason I have mentioned it here.

[7-7] A simple way to understand this effect is to recall footage of the Apollo Program's huge Saturn V booster. When a Saturn V launched, the vehicle at first rose only very, very slowly: the enormous thrust of the five engines (and the tens of thousands of pounds of propellant) was required just to hold the vehicle in place in mid-air against gravity. Those are "gravity losses."

[7-8] "GTO" – the acronym for "GEO transfer orbit" – is a highly elliptical orbit, the upper edge of which approaches GEO and the lower edge of which approaches LEO. This approach is quite common for current ELVs and upper stages that deploy communications satellites to GEO.

[7-9] As we will discuss later in this Chapter, there may also be circumstances where a smaller payload capacity might be of interest – as long as the prices are low enough.

[7-10] Stein, G. Harry, "Halfway to Anywhere: Achieving America's Destiny in Space" (M. Evans and Company, Inc.). 1996.

[7-11] There are, of course, a wide variety of alternative propulsion systems not listed here (e.g., aerobraking, rotating tethers, etc.). The focus here is on selected promising candidates that highlight key systems trade space options associated with the launch and deployment of SPS in the coming 10-20 years.

[7-12] Another AIST option that has been discussed in the past is that of deploying all or a portion of the SPS platform in LEO and allowing it to move itself from LEO to GEO (using on board SEP propulsion systems). Because of current concerns and constraints related to orbital debris in low Earth orbit, this architectural option is not considered in any detail in this book. (See Chapter 9 for additional information.)

[7-13] The discussion above is intended only to sketch twhat the limits on payload costs to LEO would be for Expendable Launch Vehicles of different sizes for launch of an SPS platform. This is not a rigorous analysis, but it is internally consistent. The analysis is based on an assumed single-stage-to-orbit ELV using LOX-Hydrogen propulsion. Of course, such a vehicle would never be built; ELVs always use two or more stages since that approach is more cost-effective in launch to LEO.

[7-14] Of course, in this discussion I have neglected all manner of other components of the Life Cycle Cost (LCC) for an SPS: including the costs of ETO transportation operations, in-space transportation, in-space operations, and various others. The key point here is that the costs of an SPS launched by ELVs cannot be less than cost of the launch vehicle hardware; this is the lower limit for the cost of a Solar Power Satellite deployed in this manner.

[7-15] Looking at Chapter 12, however, it certainly would seem that mass-produced ELVs might work for what I describe as "premium niche markets" in which the acceptable price of electricity is $2-$3 per kilowatt-hour.

[7-16] Interestingly, this implies that the number of flgihts per vehicle for deployment of a full-scale Solar Power Satellites can be lower if the RLV and its payload are somewhat smaller (implying more vehicles manufactured).

[7-17] The analysis presented here was based on the rocket equation in which the mass ratio for expendable vehicles is superior to that for reusable vehicles with the same payload, and that the mass ratio for heavy lift expendable vehicles is better than for smaller expendable launch vehicles.

[7-18] This is about ten times larger than the average module size for the actual SPS-ALPHA concept, described in Chapter 5, but it's a useful scale for our purposes here.

[7-19] The manufacturing curve (aka, the “learning curve”) used was 65%; namely, that for a doubling in the number of units manufactured, the cost per kilogram would be reduced by some 35% compared to the previous cost. This concept is discussed extensively in the preceding Chapter 6, which concerns cost estimation for SSP.

[7-20] The term “fractional expendability” referes to the inverse of the number of vehicle flights that are expected. A lifetime of 100 flights implies a “fractional expendability of 1%, and so on.

[7-21] “ERDA” was the US “Energy R&D Agency,” the name of which was changed in the US Department of Energy (DOE) by the latter years of the 1970s.

[7-22] As we discussed at the beginning of this Chapter, there are other options, of course. These include infrastructure-rich options such as space tethers and high-thrust/high-Isp options. Generally speaking, there are technology options for the farther-term; the emphasis here is on possible solutions for the near- to mid-term. Also, there is another entirely different solution for SPS in-space transportation and operations: assemble the SPS platform in LEO and require that platform to transport itself from LEO to GEO. This solution has a number of issues and one big advantage: additional in-space transportation is not needed.

[7-23] For purposes of this simplified analysis, constituent FOMs, such as fractional expendability for the OTV per flight, the probability of catastrophic failure per OTV flight, etc., are neglected.

[7-24] Note that this discusion focused on space transportation relevant to SPS. It is not comprehensive; there were various developments in the US and internationally that are not discussed here.

[7-25] The vehicle was also known as “Clipper Graham,” after the late General Daniel Graham, an important and long-time space advocate. See: http://en.wikipedia.org/wiki/McDonnell_Douglas_DC-X

[7-26] As I recall, a scale model of the SpaceLiner100 vehicle on the launch assist system was even fabricated and shown to Senator Trent Lott, graphically presenting the concept for an ambitious program to follow-on the cancelled RLV initiative.

[7-27] See:

http://www.esa.int/esapub/bulletin/bullet87/pfeffe87.htm (1996)

http://thehuwaldtfamily.org/jtrl/research/Space/Launch%20Vehicles/FESTIP-Two%20Stage%20To%20Orbit%20Launch%20Vehicle,%20Bayer.pdf.

[7-28] See: http://www.independent.co.uk/news/science/the-great-european-space-scandal-1327854.html.

[7-29] See: http://en.wikipedia.org/wiki/Deep_Space_1

[7-30] I sat through several of those discussions, which were quite depressing. The importance of low cost launch to our future in space is clear – however, the need is a long-term one. Just as is the case for initial SPS demonstrations, there is no immediate requirement for RLVs. Unfortunately, in the 2004-2005 NGLT discussions, there was no discussion of the longer-term importance of RLVs for the longer-term goals (e.g., commercial development, humans to Mars, etc.).

[7-31] See: http://tealgroup.com/index.php/teal-group-news-briefs/85-flpp-future-launcher-preparatory-program-analysis.

[7-32] See: http://en.wikipedia.org/wiki/Falcon_9; and http://nextbigfuture.com/2013/03/upgraded-spacex-falcon-911-will-launch.html

[7-33] See: http://www.reactionengines.co.uk/, http://news.yahoo.com/futuristic-british-space-plane-engine-flight-test-2020-112148075.html and http://en.wikipedia.org/wiki/Skylon_%28spacecraft%29

[7-34] See: http://xcor.com/ and http://www.parabolicarc.com/2012/03/19/lee-valentine-on-how-xcor-will-open-up-space/

[7-35] See: http://en.wikipedia.org/wiki/Boeing_X-37

[7-36] See: http://www.spacenews.com/article/launch-report/37205darpa-to-start-reusable-launch-vehicle-program

[7-37] See: https://en.wikipedia.org/wiki/Hall_effect_thruster and https://en.wikipedia.org/wiki/SMART-1

[7-38] See: http://www.nasaspaceflight.com/2013/04/gerstenmaier-expands-asteroid-mission/.

[7-39] The cost of launch on the Space Shuttle is rather uncertain, even now. Setting aside the cost of development, the cost per launch averaged about $900M, with a payload of about 25,000 kg, or about $36,000 per kilogram.

[7-40] See: http://en.wikipedia.org/wiki/StarTram.

[7-41] Glaser, Peter; "Testimony before the US Congress on the topic of Solar Power from Satellites;" (Hearings before the Subcommittee on Aerospace Technology and National Needs of the Committee on Aeronautical and Space Sciences, United States Senate; Washington, DC). 1976.

Chapter 8

Transformational In-Space Operations

"Just like everybody else, we've already looked at everything…"
Senior Aerospace Manager (1993)
at an AIAA Conference Session on Earth to Orbit Transportation

Introduction

In order for economically-viable Solar Power Satellites to be realized, it will be necessary to completely transform how we undertake the deployment and operation of large systems in space. The most ambitious space system to date is the International Space Station (ISS); with a mass of roughly 480 metric tons (about 1,100,000 lbs), the ISS required more than a decade to launch and assemble in low Earth orbit (LEO) and involved tens of thousands of individuals on the ground, hundreds of hours of astronaut extravehicular activity (EVA), and approximately 100 billion dollars (including hardware, launch and construction operations). Clearly the current state-of-the-art for in-space operations – as represented by the ISS – would not result in a commercially viable SPS. Fortunately, the dramatic changes that are needed are not only possible but can be accomplished quickly.

The preceding chapters discussed the flight hardware costs and space transportation aspects of the Space Solar Power challenge. In this Chapter, we turn our attention to the crucial new in-space operations capabilities that must be developed for SSP, including: space assembly, maintenance, and servicing (SAMS); systems autonomy; in-space refueling; and autonomous guidance, navigation, and control (GN&C), and others.

Moreover, in the longer term in-space manufacturing and in-space resources utilization (ISRU) could become increasingly valuable as a means to reduce requirements for transport from Earth to meet SPS logistics needs. ISRU might include resources from the Moon as well as those from near-Earth objects (NEOs), or it might involve the recycling of materials gleaned from an operational SPS. These options are promising, but only if development of the relevant technologies results in products that are cost-competitive with those delivered from the ground. The Chapter also takes a look at the opportunities offered by in-space manufacturing and ISRU for SSP and the constraints that such logistics must meet.

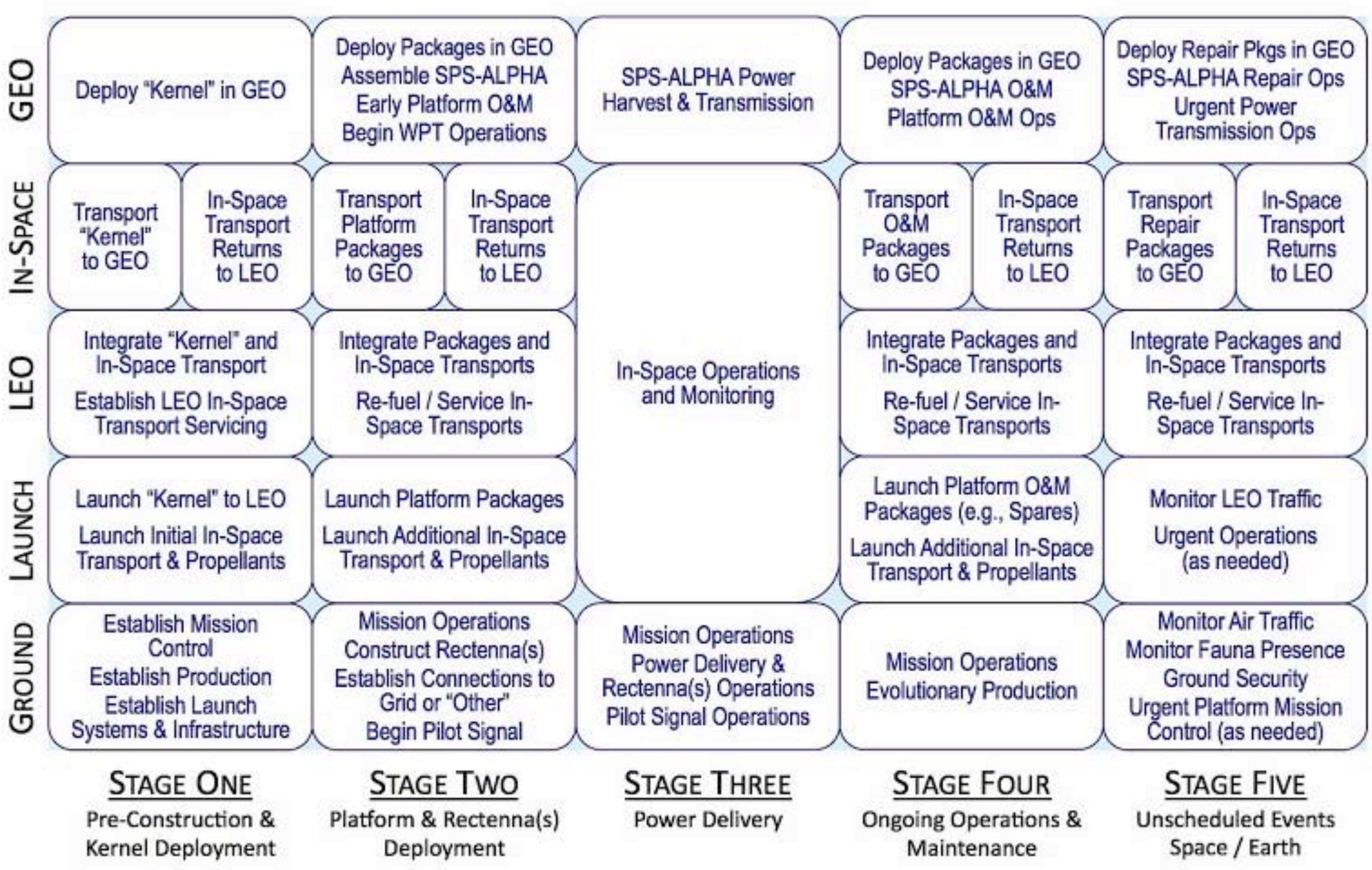
To begin, however, let's construct a framework for our discussion of transformational in-space operations for Space Solar Power by sketching a "concept of operations" (a.k.a., CONOPS) for SPS-ALPHA.[1]

SPS-ALPHA Concept of Operations

Thirty-five years ago, an explicit assumption for Solar Power Satellites was that hundreds of astronauts – working in space-based factories alongside thousands of 1970s-era robots – would be required for platform construction and operations. This presumption was entirely reasonable given the state-of-the-art in robotics and autonomous systems at that time. However, tremendous progress has been made since then. As a result, the baseline assumption for SPS-ALPHA is that <u>no</u> astronaut labor in space will be involved in either platform construction or planned repair and maintenance. This is not the same thing as saying that no astronaut support would ever be needed. For example, in the event of unanticipated events – such as damage to the platform or something unexpected arising during repair and maintenance – intervention by astronauts might well be needed.

We observed earlier that the hyper-modular SPS-ALPHA concept should resemble a living system, with several distinct types of "agents" performing various roles in the ecosystem of the platform. Metaphors to characterize the concept during mature operations include a colony of ants, a hive of bees, or a coral reef. But how would this in-space ecosystem get started, and how would it grow? The concept of operations for SPS-ALPHA will be dramatically different at several different stages of the platform's life cycle. To understand this, we need to walk through the life cycle of a typical SPS-ALPHA, beginning with the initial deployment of the first modules that will comprise the platform. Figure 8-1 provides an illustration of the overall SPS-ALPHA CONOPS.

Figure 8-1 SPS-ALPHA Concept of Operations Overview



GEO	Deploy "Kernel" in GEO	Deploy Packages in GEO Assemble SPS-ALPHA Early Platform O&M Begin WPT Operations	SPS-ALPHA Power Harvest & Transmission	Deploy Packages in GEO SPS-ALPHA O&M Platform O&M Ops	Deploy Repair Pkgs in GEO SPS-ALPHA Repair Ops Urgent Power Transmission Ops
IN-SPACE	Transport "Kernel" to GEO In-Space Transport Returns to LEO	Transport Platform Packages to GEO In-Space Transport Returns to LEO	In-Space Operations and Monitoring	Transport O&M Packages to GEO In-Space Transport Returns to LEO	Transport Repair Packages to GEO In-Space Transport Returns to LEO
LEO	Integrate "Kernel" and In-Space Transport Establish LEO In-Space Transport Servicing	Integrate Packages and In-Space Transports Re-fuel / Service In-Space Transports		Integrate Packages and In-Space Transports Re-fuel / Service In-Space Transports	Integrate Packages and In-Space Transports Re-fuel / Service In-Space Transports
LAUNCH	Launch "Kernel" to LEO Launch Initial In-Space Transport & Propellants	Launch Platform Packages Launch Additional In-Space Transport & Propellants		Launch Platform O&M Packages (e.g., Spares) Launch Additional In-Space Transport & Propellants	Monitor LEO Traffic Urgent Operations (as needed)
GROUND	Establish Mission Control Establish Production Establish Launch Systems & Infrastructure	Mission Operations Construct Rectenna(s) Establish Connections to Grid or "Other" Begin Pilot Signal	Mission Operations Power Delivery & Rectenna(s) Operations Pilot Signal Operations	Mission Operations Evolutionary Production	Monitor Air Traffic Monitor Fauna Presence Ground Security Urgent Platform Mission Control (as needed)
	STAGE ONE Pre-Construction & Kernel Deployment	STAGE TWO Platform & Rectenna(s) Deployment	STAGE THREE Power Delivery	STAGE FOUR Ongoing Operations & Maintenance	STAGE FIVE Unscheduled Events Space / Earth

Image Credit: Artemis Innovation Management Solutions LLC (2013)

At a high level, the CONOPS of an SPS-ALPHA platform would comprise various operations that may be organized into five primary stages: (1) initial deployment of a "*Kernel*" (described below); (2) deployment of the platform based on the *Kernel*, and construction of receivers on Earth; (3) power delivery to Earth; (4) ongoing operations and maintenance (O&M); and (5) dealing with unscheduled events.[2] Each of these stages involves operations that are in common with others as well as some that are unique. In turn, each of these stages in the life cycle involves activities in one or more of five different domains, including: (a) operations on the ground; (b) launch operations; (c) low Earth orbit (LEO) operations; (d) in-space transportation; and (e) geostationary Earth orbit GEO) operations.

Next, we'll discuss each of the several stages in turn.

Stage 1: Pre-Construction and Deployment of an SPS Platform Kernel

As we'll discuss in Chapter 10, the programmatic strategy for SPS-ALPHA involves a series of increasingly complex and capable Design Reference Missions (DRMs), beginning with small technology flight demonstrations (TFDs) in LEO and proceeding through the mid-term with an integrated SPS-ALPHA "pilot plant" in GEO. If this strategy is followed, then the ground-based elements of Stage 1 of the CONOPS for a full-scale platform – including enabling production, establishing mission control, etc. – should be well in hand by the time Stage 1 begins. Figure 8-2 presents a more focused view of Stage 1 of the concept of operations.

As currently conceived, SPS-ALPHA construction would begin with the deployment of a "Platform Kernel" – in other words, a preliminary space platform capable of self-sufficient operations, station keeping, communications, etc. (The ISS assembly sequence followed this general initiation approach.) The Kernel might comprise perhaps one-half of one percent (about 0.5%) of the full-scale platform – i.e., approximately 100 metric tons (MT), or about one-quarter to one-third of the mass of the ISS. This Kernel would resemble – at a smaller scale – the SPS pilot plant (aka, "DRM-3" as described in Chapter 10). It would comprise all of the several module types involved in SPS-ALPHA, with a preponderance of robotics and propulsion-related modules. This platform Kernel would provide the anchor point for all subsequent payload delivery missions and assembly operations. It would provide needed station-keeping propulsion, structural systems to enable mobility by robotic systems (in particular the MAREs described in

Chapter 5), initial power for operations, etc. The total duration of Stage 1 would nominally be about three months.

Figure 8-2 CONOPS Stage 1: Pre-Construction & Deployment of the *Kernel*

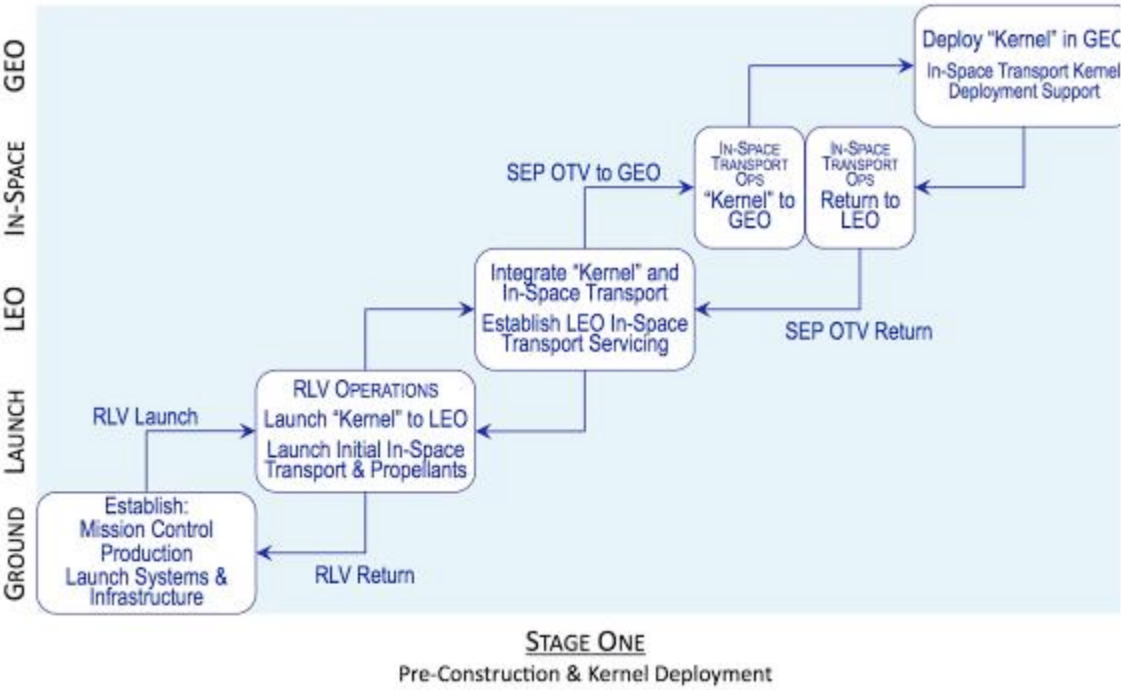


Image Credit: Artemis Innovation Management Solutions LLC (2013)

As illustrated, Stage 1 would also involve the initial deployment of the reusable in-space transportation systems we discussed in Chapter 7. If the mass of the Kernel is approximately 100 MT, then a moderate capacity RLV should be able to launch it and the propellant required to transport the piece parts to GEO in some six or seven Earth-to-orbit missions. In turn, two more flights of a SEP OTV could transport the still-packaged pieces of the Kernel from LEO to GEO. Although designed to be reusable, at least one of these vehicles would most likely stay with the Kernel in GEO, providing important functions during initial deployment such as station keeping, communications, power, etc.

Clearly, a high degree of systems autonomy and autonomous navigation (including rendezvous and docking) will be essential. If large ground crews and teams of sustaining engineers are required, the costs will quickly become unsustainable. This is true (increasingly so) for all stages of the concept of operations. However, the level of robotics technology required should be readily achievable: a key to the SPS-ALPHA concept is that all of the modular pieces will be ‘tagged’ in multiple ways (e.g., bar codes, RFID, visual cues, etc.). The operational environment for onboard robotics will be extremely well structured, just as is the case for the structured, pheromone-rich environment of a beehive or ant colony.

With the completion of Stage 1, all the major elements of the architecture will have been deployed and validated – including pre-launch logistics, mission control, and space transportation systems. In addition, a platform of about 100 MT will be operational, in or near GEO for the beginning of the next stage: platform deployment and ground receiver construction.

Stage 2: Platform and Receiver Deployment

Following the initial SPS platform *Kernel* deployment, the second stage of the SPS-ALPHA life cycle would begin: in-space assembly and construction (ISAAC) of the full platform in tandem with construction of one or more receivers on Earth. This stage would represent the period of greatest activity for transportation to, proximity operations around, and construction on the emerging SPS. For economic reasons, the goal must be for the ISAAC second stage to require no more than one or two years to complete. These years represent the period of greatest expenditure and must be followed as soon as possible by the beginning of revenues. The details of the SPS-ALPHA platform concept were provided in Chapter 5. Figure 8-3 illustrates this aspect of the overall concept of operations.

In addition to in-space operations, during this stage one or more ground-based receivers would be constructed and connected to the local power grid. With this deployment early during Stage 2, testing of the end-to-end wireless power transmission system would begin in preparation for full-scale power transmission during Stage 3.

The scope of Stage 2 is truly stupendous when compared to traditional space missions and operations. Over the span of approximately two years, a total of about 20,000 metric tons of SPS hardware will need to be transported from factories on Earth to geostationary Earth orbit. If the ETO payloads are about 20 MT each, and (based on the LEO-to-GEO assumptions explained in Chapter 7), if roughly two launches of propellant are required for every three launches of platform hardware, then a total of about 1,700 ETO missions will be required during Stage 2.

Figure 8-3 CONOPS Stage 2: Platform and Rectenna Deployment

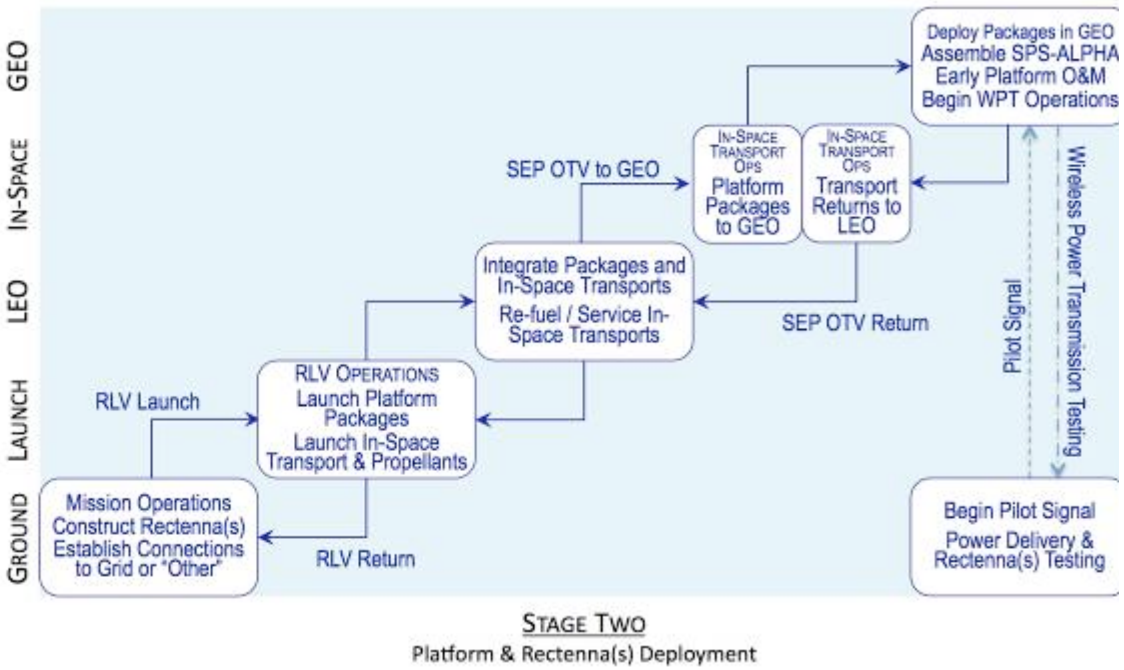


Image Credit: Artemis Innovation Management Solutions LLC (2013)

And, at 50 MT of payload per flight, roughly 400 LEO-to-GEO missions will be needed. Assuming assembly over two years, the result per week would be a bit more than 16 ETO launches, and a bit less than 4 LEO-GEO missions. If this choice is made, needless to say, a substantial fleet of RLVs and reusable OTVs would be needed to accomplish this deployment. Are such enormous mission-focused operations even possible in aerospace? By way of comparison, two examples are useful; the first is a modern example, the second is from World War II.

Consider the airfield operations at Memphis International Airport, the home of the rapid freight delivery firm "Fedex Express" (formerly "Federal Express"). In 2009, this single airport in Tennessee handled 3,698,000 MT of airfreight – roughly equivalent to more than 180 full-scale Solar Power Satellites.[3] Airports around the world, such as Hong Kong, Shanghai's Pudong International Airport, Dubai International Airport, and others followed close behind. The point being that the scope of logistics required for a single full-scale SPS-ALPHA, at some 20,000 MT over two years, is a tiny fraction – less than one percent – of the capacity of modern airfreight services at a single airport.

The second example is an historical one. In the waning days of World War II, Nazi Germany, having lost control of the skies, turned to automatic, long-range weapons to strike at the Allies, particularly the UK: the V-1 aerial drone-bomb, and the V-2 ballistic missile. Over the course of six months (from September 1944 to March 1945) more than three thousand V-2 rockets were manufactured and launched against targets in five countries – a rate equivalent to roughly 6,000 launches per year, more than 100 launches per week, or about 16 launches per day.[4] Of course, there are vast differences in the payloads, the level of technology, and the complexity of the vehicles involved. However, the comparison is instructive: over 5 times more launches per week during WW-II, some 70 years ago, than would be required for deployment of a full-scale SPS-ALPHA in two years.

The scope of the operations required to accomplish Phase 2 of the SPS-ALPHA CONOPS is an order of magnitude or more greater than anything undertaken before. However, it is not unthinkable.

In contrast, the construction of the ground WPT-receiving Rectennas would be relatively straightforward. Although these receivers will be large – perhaps as much as 10 km (6 miles) in diameter – they are quite simple. The Rectenna-based receiver is far simpler than a PV array or Concentrator Solar Power (CSP) of comparable capacity. A Rectenna would comprise millions of small antennas, each approximately 15 cm (or about 6 inches) in size; it would likely be pre-fabricated in automated factories and deployed in large sections to be later connected to one another and to the grid.

Stage 3: Power Delivery Operations

The third stage in SPS-ALPHA operations would be the first that generates revenues and profits for the full SPS platform: delivery of power to markets on Earth. Stage 3 would involve regular, largely autonomous mission operations for the in-space platform, Rectenna operations at one or more locations on Earth, including pilot signal transmission to the platform in orbit. It would also involve in-space operations and monitoring to track possible objects that might intersect the power transmission, and SPS platform operations associated with power harvesting, conversion and microwave wireless power transmission (WPT). Figure 8-4 presents an overview of Stage 3 of the CONOPS.

A key technology for SPS-ALPHA power delivery operations is retrodirective phase-controlled WPT, which we touched upon in Chapter 4. With this technique, a pilot signal from the receiving site is essential; it continuously delivers a phase reference to the many modular transmitters in the primary array of the platform. Although little known, the basic technologies for retrodirective WPT are well understood and have been demonstrated many times. (See the discussion in Chapter 3.)

Figure 8-4 CONOPS Stage 3: Power Delivery Operations

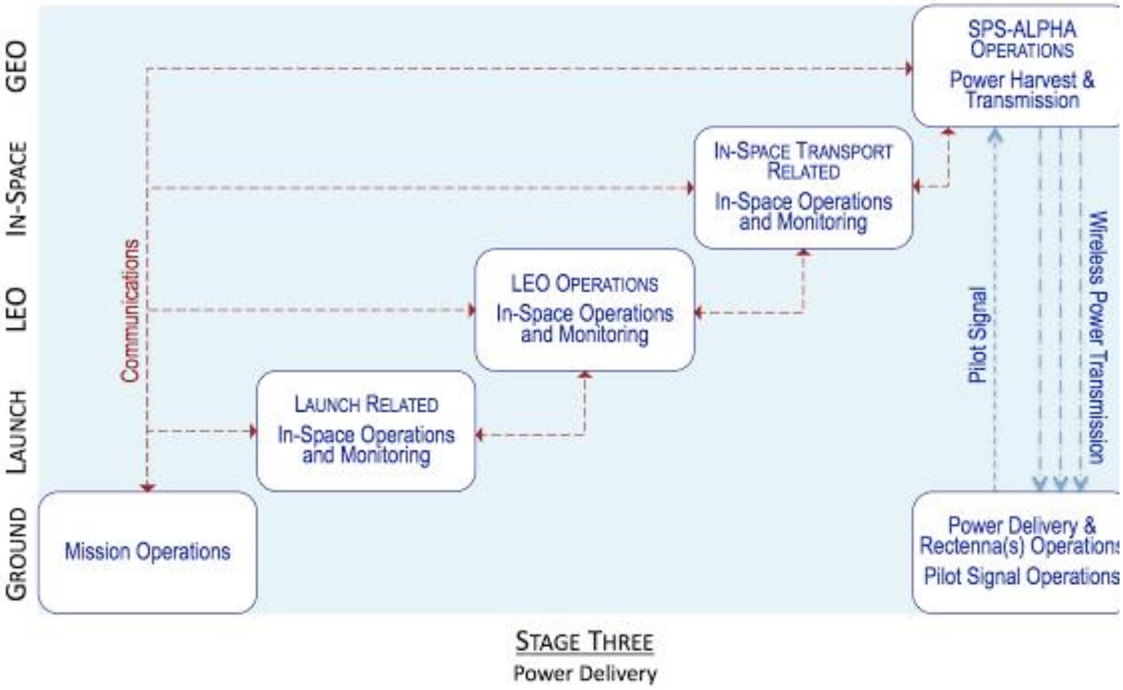


Image Credit: Artemis Innovation Management Solutions LLC (2013)

In addition to energy harvesting and power delivery, the SPS would quite probably also generates revenue by hosting commercial or government payloads on a leased services basis. These could include weather observing, communications payloads, asteroid early warning systems, etc.

Stage 4: Ongoing Operations & Maintenance

The fourth stage of the CONOPS – on-going operations and maintenance (O&M) – would comprise several distinct types of operations, including: (1) mission operations; (2) launch and in-space transportation missions; (3) scheduled repair and maintenance operations; and (4) platform propulsion systems refueling. While Stage 3 operations continue, and starting early in the CONOPS, Stage 3 (ongoing O&M) would begin. A central tenet of the concept of operations is that the SPS-ALPHA platform is similar to large hydroelectric plants; they would essentially never be decommissioned. Instead, the concept is that the platforms would be continuously renovated. Figure 8-5 presents a high-level depiction of the CONOPS for Stage 4.

Figure 8-5 CONOPS Stage 4: Ongoing Operations & Maintenance

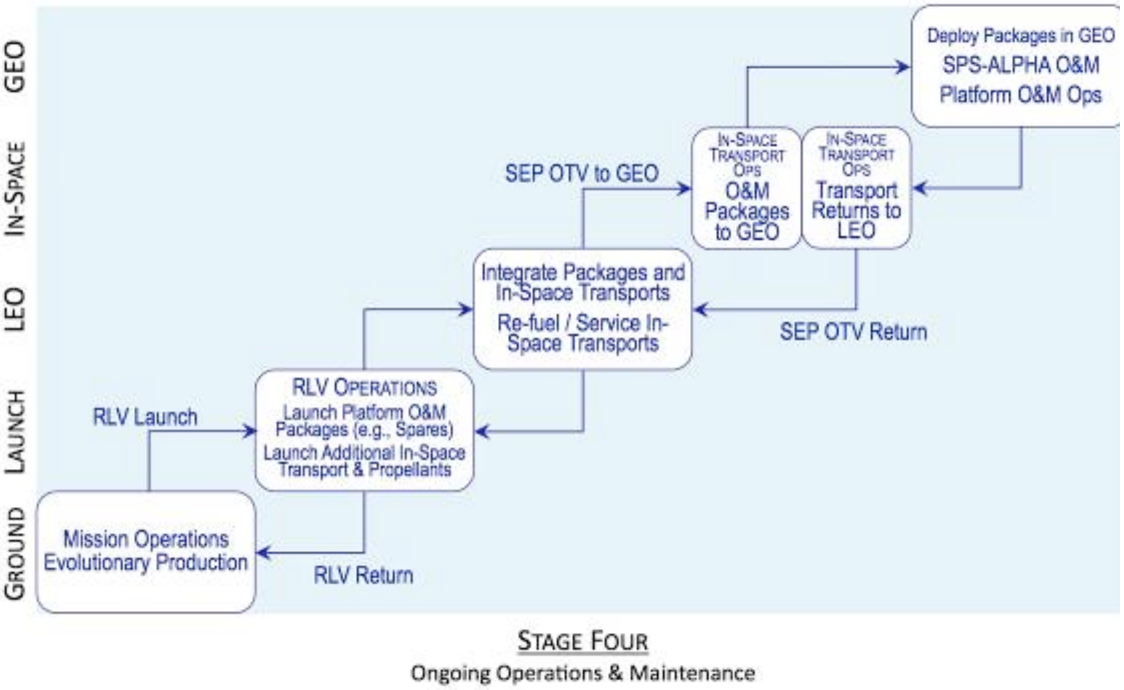


Image Credit: Artemis Innovation Management Solutions LLC (2013)

As a general input to the SPS economic analysis discussed later, the average lifetime of an individual SPS-ALPHA module was “guesstimated” to be 30 years ± 10 years, and that each year – beginning in year 10 of operations – that approximately 3% of the modules on the SPS platform will be replaced and/or repaired. If about 3% of a roughly 20,000 MT SPS is replaced each year, then something like 600 MT must be transported to GEO annually, or about 50 MT every month. (Adding propellant, this is equivalent to approximately three flights per every two weeks for the RLV discussed previously in this Chapter.) This level of refurbishment logistics would be quite manageable – essentially when compared to the scope of operations during deployment (Stage 2).

Moreover, if a substantial fraction of the materials that might be recovered from failed modules could be recycled and used again, then the long-term economics for Space Solar Power might be substantially improved.

Stage 5: Dealing with Unscheduled Events

In addition to the four primary stages of the SPS-ALPHA life cycle described above, provision must also be made for dealing effectively with unscheduled – but not necessarily unexpected – events. These include inevitable events that will happen during the lifetime of the platform, such as an unscheduled traverse of the WPT transmission by an aircraft flying too near a receiver, a spacecraft in a lower orbit, or the impact of a large solar particle event (SPE) – i.e., a solar flare – on the platform. Unscheduled events also include those that might happen, such as physical or cyber threats to the SPS. Figure 8-6 presents an overview of this final, unscheduled stage of the CONOPS.

Figure 8-6 CONOPS Stage 5: Dealing with Unscheduled Events

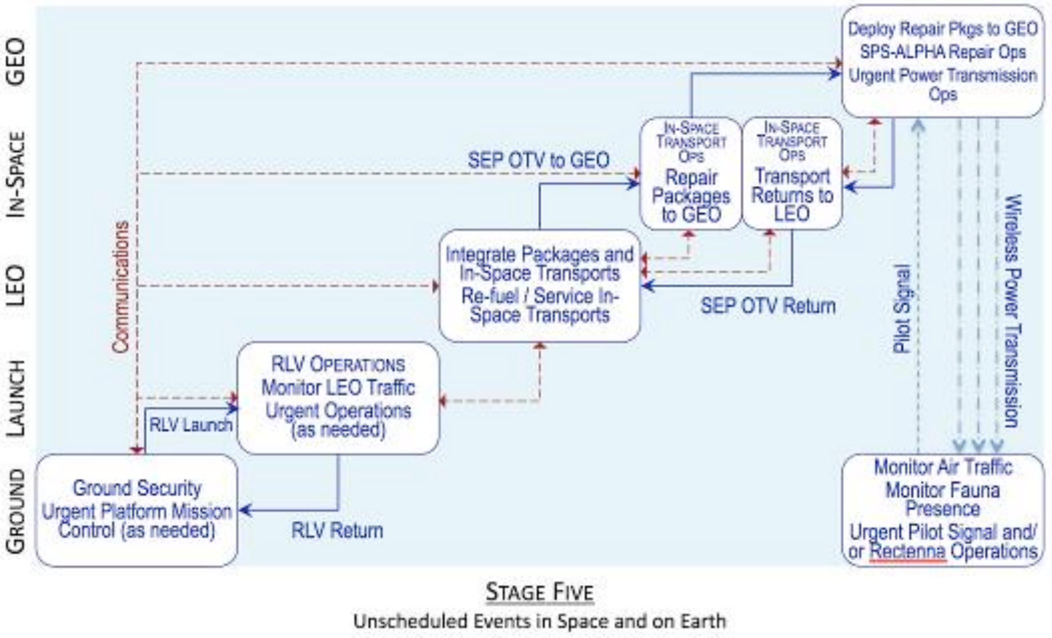


Image Credit: Artemis Innovation Management Solutions LLC (2013)

Although the baseline CONOPS for SPS-ALPHA does not involve any astronaut involvement in LEO or GEO, it is only prudent that Stage 5 should provide for the possibility of astronaut intervention to deal with unanticipated (potentially unstructured) events. The details of these operations will depend entirely, of course, on the capabilities that are available when needed.

Now, let’s discuss in brief some of the technological capabilities that will be necessary to implement the ambitious concept of operations described in the preceding paragraphs.

Needed Capabilities

There are two basic topics to be addressed in identifying the capabilities needed to accomplish the CONOPS we’ve just discussed. First, what are the requirements for operations and maintenance in terms of cost? Second, what are the technologies that must be advanced to satisfy those requirements? Earlier chapters spoke primarily about the costs of hardware and of space transportation for Space Solar Power. However, the cost of every person working on O&M

or sustaining engineering for an SPS contributes to the cost of electricity. As a result, another consideration of importance is that of the personnel required for ongoing operations.

Let's start by looking at two general approaches to operations and maintenance: the International Space Station (ISS), and small satellite constellations (both in LEO).[5]

International Space Station

Large, monolithic architectures such as that of the ISS entail a substantial requirement for O&M and sustaining engineering activities, with many different systems, from a wide variety of countries to be operated safely. In the US alone, the annual budget for the International Space Station is about $2.5 billion, which of course includes a great many expenses not directly related to O&M. For the sake of simplicity, let's assume that (1) the annual cost attributed to operations and maintenance is $1B (a number that may be low, but is not likely to be high), (2) the cost per full time equivalent (FTE) is $85,000 per year, and (3) the total mass of the ISS is 450 MT. Then, as shown in the figure, the annual O&M labor works out to be roughly 26 FTE per MT. If these O&M rates are applied to a full-scale SPS (assumed at a mass of 20,000 MT and power delivered of 2 GW), then the contribution due to O&M labor alone to the cost of electricity would be about $2.50 per kilowatt-hour.

Small Satellite Constellations

However, if the operations model is more analogous to those of typical small satellite constellations in LEO, then the situation changes significantly for the better. Drawing on data from current SmallSat constellations (with constellations from 30-60 satellites, masses from 50 to 750 kg, and personnel ranging to the several hundreds), then the O&M / sustaining engineering labor works out to be approximately 0.05 FTE per MT. If the O&M rates for an SPS (same assumptions as above) are comparable to these, then the contribution due to O&M labor to the cost of electricity would be about less than 1¢ per kilowatt-hour. Figure 8-7 illustrates the challenge that must be overcome.

Figure 8-7 The Importance of Autonomous Operations for SSP

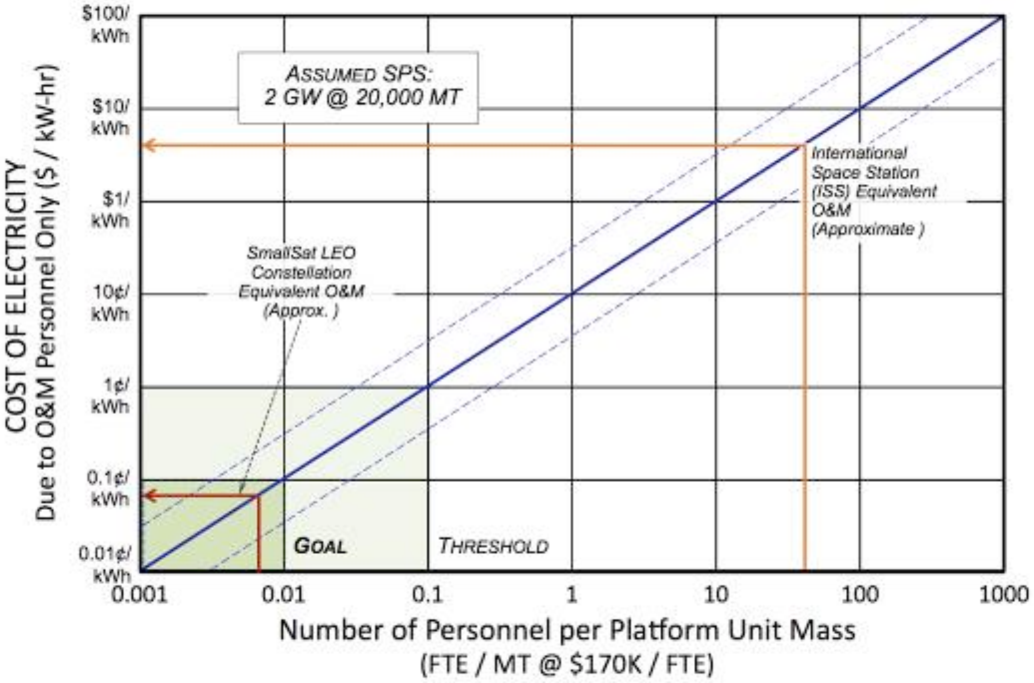


Image Credit: Artemis Innovation Management Solutions LLC (2013)

There are likely several reasons for this difference. First, the ISS is a large, monolithic system and involves complex operations on orbit. Second, the piece parts of the ISS came from various countries and involved hand-assembled interfaces (in some cases). In addition, the ISS is a human-rated, inhabited system. Finally, the ISS is a mission-driven, government program as compared to a profit-driven commercial venture.

Summary of the Challenge

The challenge is to succeed in making the operations and maintenance for SPS-ALPHA almost entirely autonomous with minimal operator supervision; the number of personnel on Earth in sustaining engineering or in mission control must be comparable to those of low cost commercial constellation models. Figure 8-7 illustrates the challenge that must be overcome. Of course, the concept of operations for SSP is much more complex that that of a SmallSat constellation in low Earth orbit. The challenge for economically viable SPS is to achieve complex large-scale space operations with the same level of personnel that a much more modest mission would require.

Let’s discuss next some of the technology advances that are essential to achieving that goal.

Technology Challenges

Of course, the strategic CONOPS described at the beginning of this Chapter depends on Earth-to-orbit and in-space transportation capabilities, discussed in Chapter 7. In addition, a range of new systems and technologies will be required to enable the concept of operations. The following are some of the most important non-transportation in-space operations capabilities that must be developed for SSP:

- Autonomous Guidance Navigation and Control (GN&C);
- Autonomous In-Space Refueling;
- Systems Autonomy;
- Space Assembly, Maintenance and Servicing (SAMS);
- Reconfigurable Wireless Networks; and,
- Retrodirective Phase Control Wireless Power Transmission.

As we discussed in the introduction to this Chapter, two additional capabilities are potentially very important, but yet to be proven capability for the concept of operations: in-space resources utilization (ISRU) and Systems Recycling.

The following paragraphs provide a rough sketch of the transformational, new, in-space operations capabilities that will be needed. (Chapter 15 discusses the detailed technology readiness and risk assessment for these technologies.)

Autonomous Guidance, Navigation & Control

The SPS-ALPHA concept involves literally hundreds of thousands of modules and hundreds of LEO-to-GEO deployment missions. Autonomous guidance, navigation and control (GN&C) is enabled for this functional capability for SPS-ALPHA – and any other economically viable – Solar Power Satellite concept. Key O&M phases include autonomous guidance, navigation and control during a variety of vehicle operations, including autonomous rendezvous and docking (AR&D), vehicle “reboost,” LEO-to-GEO transportation missions (and vehicle return to LEO), and GEO operations such as platform station keeping.

Some of these functions have been validated in aircraft operations or in selected SPS mission operations. For example, NASA's Deep Space 1 mission (which we touched upon in Chapter 7) demonstrated an early version of autonomous navigation, among other technologies. Certainly, the ongoing operations of various unpiloted vehicles – including the Japanese, European, and US commercial cargo vehicles that travel to the ISS – have demonstrated the key capabilities that are needed. However, additional development is needed for SPS-ALPHA space operations, particularly to ensure that the end-to-end operational environment is well integrated and robust in the event of unanticipated events. At present, there are no evident showstoppers in the required capabilities, although early and continuing demonstrations of these capabilities will be needed.

Autonomous In-Space Refueling

Refueling is an essential, albeit secondary, capability that enables the re-use of vehicles on Earth (or in space). Space transportation systems cannot be made reusable, and platforms in orbit cannot be operated over long periods of time without refueling in space. This challenge relates more to a specific set of technologies than the others in this list; however, the impacts of refueling (or of not being able to refuel) are pervasive. This is certainly true in the case of Space Solar Power. Of course, the economic value of refueling is inversely proportional to the fuel efficiency of the propulsion system involved; however, for any realistic system, refueling is vital.

In the baseline concept for SPS-ALPHA, a common solar electric propulsion system (SEPS) would be used for both platform station keeping and LEO-GEO transportation. Refueling of these systems – in LEO for the transport and in GEO for the platform – is enabling for SPS. As with other key O&M functions, in-space refueling needs to be as autonomous as possible. It is "to be determined" whether this type of refueling would be more cost-effectively handled by tank replacement or by fluid transfer. In the case of tank transfer, requirements for new technologies will be minimal; in the case of fluid transfer, R&D is definitely needed (although the fluids to be managed are not difficult). Also, if the tanks are a relatively small fraction of the total mass, it may well prove that returning them to Earth for refurbishment and refill is an interesting option. (Recall that the RLVs launching SPS parts will return essentially empty; the return of the empty tanks might prove to have little impact on costs.)

Systems Autonomy

Systems autonomy – i.e., the capability for a system to operate and respond to events with minimal intervention by operators or ground-based support personnel – is a secondary driver when compared to the cost of spacecraft hardware or the cost of space transportation. But as we discussed above, it can become significant for large and long-lived systems such as an SPS. During the course of mission operations, the number of personnel working as full time equivalents (FTEs) can be an important driver of life cycle cost (LCC). The principal roles for these persons can typically include: (a) mission operations; (b) sustaining engineering (including engineering staff required for software operations and maintenance); and (c) overhead or management staff. Key drivers for SPS platform and operations autonomy will concern the technology that can be incorporated in a pervasive fashion into essentially all SSP systems (e.g., in onboard computing, sensors, avionics, etc.). Platform responsiveness to unanticipated events (e.g., a micrometeorite impact) is particularly critical.

Clearly, significant improvements will be required beyond the level of autonomy that characterizes most current space systems. As we saw above, platform and operations autonomy can be make important contributions to reducing space mission life cycle costs by reducing the number of ongoing personnel involved.

Space Assembly, Maintenance, and Servicing

Space assembly, maintenance, and servicing (SAMS) of one sort or another is enabling for any space systems concept that is larger than the payload of the largest existing or planned ETO transportation system. This was certainly true for the ISS, for which many launches of various vehicles have been required; it will be true for future, more ambitious, human space exploration missions such as a lunar outpost or a human mission to Mars (HMM). The most important question vis-à-vis SAMS for SPS is whether or not one or more stand-alone, dedicated, orbiting construction platforms are needed to enable a specific SPS architecture. For example, in the case of the SPS 1979 Reference System architecture (see Chapter 4), dedicated platforms in both LEO and GEO were required. However, in most concepts developed since the mid-1990s, a greater or lesser degree of "self-assembly" is typically assumed.

The SPS-ALPHA more or less goes "to the limit" – the full-scale SPS platform would be composed of literally millions of smaller, self-assembling modules. Nevertheless, the challenge of SAMS for SPS-ALPHA type appears to be entirely feasible from a technical point of view. How can this be true?

Many have marveled at the deliberate, seemingly inexorable accomplishments of recent planetary surface robots ("rovers") in traversing and studying the surface of Mars. Since the 1990s, it has been evident that robotic operations in an unstructured (and sometimes hazardous) environment must be cautious and carefully controlled. And therein lies the central difference – the environment onboard an SPS will not be unstructured. Instead, as is the case with warehouse robotics, mining robotics and automation, or factory robotics (circa 2013), the space assembly, maintenance, and servicing to be performed on an SPS platform will take place in a very highly structured environment. RFID (radio frequency identification) chips and bar codes indicating identity will be placed on essentially every object on an SPS platform. Every part of a large, hyper-modular SPS will report (when asked) the status of its operational "health," key performance details (e.g., solar array efficiency, temperature at various locations, etc.), and summary operations and maintenance (O&M) data (such as expected lifetime). Visual cues (e.g., textured or tinted surfaces) will enable determination of orientation, distance and relative motion to be determined.

As we discussed (CONOPS, Stage 4), for purposes of macroeconomic systems analysis, the recently completed NIAC Phase 1 study assumed that an average of five percent (5%) of the total SPS-ALPHA platform mass would be replaced annually as part of planned repair and maintenance operations. That works out to something like 600 MT per year for a platform of 20,000 MT. If the average module has a mass of 25-50 kg, then approximately 60 modules will need to be repaired or replaced daily – an entirely tractable "load."

There are several promising system options for SAMS. Teleoperated robotic capabilities for SAMS that can be readily anticipated in the near-term are consistent with the ambitious functionality for SPS assembly and operations. In addition, fully autonomous robotics also may be achievable if they are implemented in highly structured environments. In other words, autonomous robotics could be implemented soon if done with adequate techniques such as RFID tags, beacons, visual cues, and regular features for image recognition. The development of such SAMS systems would require explicit coordinated design with existing space structural systems technologies (e.g., kinematically-deployed structures), as well as concurrent design of new interconnects, avionics and platform dynamics, and attitude control systems.

A number of hurdles must be surmounted, of course, and some of these are significant. For example, excessive mass and cost for SAMS systems and related interconnects may be highly detrimental to overall SPS economics. These issues must be examined in greater detail by future studies. Overall, it is important that SAMS technologies be developed in close coordination with the development of SPS platform and space transportation systems and technologies, including materials and structural systems, interconnects, and controls structures interactions (CSI) technology. In the farther term, large space systems such as SPS will likely be increasingly capable of SAMS involving unstructured environments, enabling fully autonomous operations.

Reconfigurable Wireless Networks

During the course of the deployment of SPS-ALPHA, the configuration of the platform and its operational environment will of necessity change almost constantly. Wireless and automatically reconfigurable networks are commonplace on Earth, but have not yet been used in any space system. The hyper-modular architecture that is the foundation of SPS-ALPHA will depend upon the successful application of this technology.

Retrodirective Phase Control Wireless Power Transmission

The capability to ensure that power is transmitted cost-effectively and only to the appropriate location on Earth, a system such as retrodirective phase control WPT is needed in the baseline. This technology ensures that the coherent transmission can only occur toward the pilot signal transmitter. In addition, it should be tractable to encode additional data on the pilot signal (such as encrypted keys) that prevent any attempt to interfere with the transmission. Finally, the end-to-end pilot signal-transmitter system must be designed such that power transmission will cease if the field of view is about to be crossed by a satellite in a lower orbit or by an errant aircraft.

In-Space Resources Utilization

In the longer term, the use of resources that may be found in space – including near-Earth objects (NEOs) or the Moon – will become essential to commercial development and eventual settlement in space. Early applications of ISRU-derived materials and system replacement parts are likely to be straightforward in character (for example, propellants, simple structures, and similar logistics).

There are a variety of consumable materials and system hardware elements that comprise SPS-ALPHA that might be produced from ISRU, including both the Moon and NEOs. These include in the nearer-term propellants and simple spare parts; and, in the farther-term more complex parts such as structural elements, reflectors, and others. And at times, some have argued that SPS will not – perhaps cannot – be developed until ISRU systems are available in space and the platforms can be fabricated entirely from extraterrestrial materials. The most comprehensive version of this position is "Lunar Solar Power" (LSP), discussed in Chapter 4, in which SSP elements are fabricated from lunar materials and installed as systems on the Moon's surface.

The basic line of argument that leads to this conclusion relies on the assumption that space transportation cannot be made cheap enough to ever compete with terrestrial energy sources. As discussed in Chapter 7, although this is a rather controversial topic, it is my opinion that reusable launch systems can – at high launch rates – reach costs low enough to achieve Space Solar Power for Earth at roughly 10¢ per kilowatt-hour. However, in the farther term, a variety of ISRU technologies may prove extremely valuable for an SSP industry.

Systems Recycling

An important question for Stage 4 of the CONOPS that has not as yet been explored is that of recycling. As presented, the economic analysis you will see in Chapter 13 does not involve any reuse of the materials gleaned from the platform during regular Stage 4 operations and maintenance. However, it seems likely that replaced SPS-ALPHA modules – some 1,000 MT annually – would inevitably be exploited as a rich source of raw materials. Relevant technologies (discussed above) such as additive manufacturing (i.e., 3D printing) in zero gravity should make it possible to fabricate a wide variety of new systems from the "cast-offs" of an SPS-ALPHA.

In summary, over time, the failed modules of the SPS would almost certainly become the feedstock for in-space manufacturing of SPS spare parts and consumables or other systems. It seems to be inevitable that once a kilogram of Aluminum, Silicon or Carbon composite materials is transported to GEO it will <u>not</u> be allowed to go to waste.

Summary Observations

Dramatic advances in our capabilities for in-space operations must occur to realize economically viable SPS. These advances are also essential to many ambitious future goals in space exploration, science, and development. Fortunately, the capabilities needed in space are those that are taken for granted here on Earth: reusable systems; refueling; construction and maintenance; and intelligent systems that configure themselves and operate largely autonomously.

The level of personnel that are today required for large space systems such as the ISS is orders of magnitude too great for the economic requirements of Space Solar Power. The level of staffing common for SmallSat constellations in LEO is solidly in the range needed for SPS. However, the operations demanded by SPS are far more complex than those of such constellations. The key improvements needed involve the successful transition of technologies that are in use by terrestrial applications (such as automated warehousing, reconfigurable wireless networks, etc.) to modular space systems. It is my hope that you will be persuaded when you finish this volume that such transformational in-space operations are not only possible, but that they involve no fundamental breakthroughs in technology.

These advances are needed beyond the requirements of SSP. If it costs 10s of billions of dollars to land a person on the Moon or Mars, very few will ever go. The kinds of transformational in-space operations discussed here would make possible – and affordable – a broad range of ambitious future goals for space science, human exploration, and commercial development. A settlement on the Moon, construction of huge telescopes capable of imaging Earth-like planets around nearby stars, or the human exploration of Mars or the Solar System beyond; all of these visionary future goals require the transformational new in-space operations capabilities that are needed for SPS-ALPHA.

Next, let’s talk about some of the important, largely non-technical issues that must be resolved. These involve policy matters, the environmental impacts and/or benefits of SSP, and health and safety concerns that must be addressed.

[8-1] The differences between the in-space operations that would be required for the various Solar Power Satellite concepts presented in Chapter 4 are so great that they cannot be readily bridged in a succinct discussion. Here, we’ll focus on the concept of operations (CONOPS) for SPS-ALPHA, although along the way there will be information releveant to the CONOPS for other SSP approaches.

[8-2] The first four stages are rather like the ‘Acts’ in a dramatic performace: there will be ‘actors’ performing in each *Act*, and a progression of the storline. The final, fifth *Act*, however, is more like the collection of understudies in the ensemble: waiting for the unexpected to occur, and the chance to perform.

[7-3] See: http://www.ttnews.com/articles/basetemplate.aspx?storyid=23714

[7-4] See: http://en.wikipedia.org/wiki/V-2_rocket

[8-5] Detailed O&M costs are quite difficult to obtain from public data; for relevant information used in this discussion, see: http://www.airspacemag.com/space-exploration/iridium.html; http://www.satellitetoday.com/twitter/Iridium-Renews-Long-Term-O-and-M-Partnership-With-Boeing_34632.html; http://en.wikipedia.org/wiki/Orbcomm; and http://www.nasa.gov/pdf/750614main_NASA_FY_2014_Budget_Estimates-508.pdf

Chapter 9

Policy, Environmental and Safety Concerns

"Rail travel at high speed is not possible because passengers, unable to breathe, would die of asphyxia."

Dionysius Lardner1 (c. 1820s)
Irish Science Writer

Introduction

Developing Solar Power Satellites will involve solving not only tough technical challenges like those we've discussed but also a broad range of policy and regulatory issues. In addition, the opinions of specific leaders and the politics of key countries must be considered. These elements include: (1) space policies; (2) energy policies; (3) environmental and climate related rules; (4) technology research and development (R&D) program plans and international technology transfer restrictions; (5) policies concerning tax and/or incentives vis-à-vis space development or energy; (6) defense and security issues; (7) various factors related to the regulatory environment; and, of course (8) international relations and related concerns. These are topics that involve a diverse set of distinct, sometimes interrelated issues.

There are also the basic questions of wireless power transmission (WPT) safety and any possible health risks when operating as designed. For example, can the power transmission be made "fail-safe" in the event of an unintentional operational mishap (i.e., an accident)? Some of the issues involving WPT health and safety include short-term illumination of humans and other animals by the transmission. Others concern potential effects of long-term illumination of plants or animals by wireless power. Other questions involve the challenge of dealing effectively with transient illumination of electronic devices or other machines by the transmission. Of these health and safety issues, the foremost consideration must be to eliminate any possible risk to eye safety for humans and other fauna.

There is also the issue of whether the WPT system might be subverted from its intended purpose of power delivery and used as a weapon. There is also the question of what effect Space Solar Power would have on Earth's environment. Would SSP truly be "green?" Would it reduce or increase the risk of anthropogenic global climate change? After all, energy from the Sun that would otherwise bypass Earth would be intercepted by an SPS platform and transmitted to the ground. Would the fabrication and launch of a Solar Power Satellite into space cause significant negative impacts on Earth's environment?

This Chapter walks through some of the policy and regulatory issues that must be resolved, as well as environmental impacts, and the potential heath and safety concerns. All of these must be addressed if Solar Power Satellites are to be not only technically possible and economically viable, but also programmatically and politically achievable.[2]

Policy Considerations

International Cooperation

At a minimum, achieving the vision of SSP will require the international cooperation and coordination necessary to realize the orderly, economic, and efficient construction and subsequent operation of Solar Power Satellites. Only by establishing an appropriate international "regime" for SPS that is accepted by multiple countries and comprising new legal ground rules, specific programmatic relationships and existing relevant regulations may the goal be achieved. In addition, individual countries frequently formulate policies, regulations, and programs that are intended to restrain or promote specific technology R&D activities, particularly those related to national security, targeted industries, or the assurance of domestic competencies. International cooperation will be needed to ensure that such actions by individual countries do not prevent SPS development.

National and international policies, agreements, and programs are established to advance both the economic and the security interests of the countries involved, while commercial firms – although they may be players nationally and internationally – are typically driven solely by the financial interests of their owners or stockholders. In addition to existing agreements that must be satisfied, it is likely that new agreements will be needed to establish the international environment within which governments, commercial firms, and other players may pursue SSP technology and later SPS systems development. Specific international regimes are typically created through treaties between two nations, or among multiple countries for common purposes under which the participating states agree to abide by the agreed-upon rules. The agreement under which the International Space Station has been implemented is one obvious example, with its emphasis on government-to-government cooperation. Some SSP advocates have argued for the creation of an internationally organized, government-owned corporation for SPS development, analogous to the COMMSAT (the Communications Satellite Corporation) and INTELSAT (International Telecommunications Satellite Consortium) organizations of the 1960s.[3] This approach might indeed be very constructive in the event that the rivers of SPS development are national organizations such as JAXA, ESA, CAST, etc. However, until there is a broad international consensus that SPS is both feasible and should be developed – as was the case with communications satellites in the 1960s – in my view it is premature to pursue this approach.

For obvious reasons, during the past 60 years space-related matters have been of special national and national security importance. "Space" has been pursued in the context of an international regime created in large measure through United Nations (UN) sponsored international space treaties and some other agreements. Future SPS systems must operate within this existing regime, as it may be modified by future agreements and regulations. Some of the most relevant elements of the existing international regime for space activities and their implications for SSP (i.e., current international treaties, including the Outer Space Treaty of 1967) are outlined in Table 9-1.

The UN General Assembly established an important player in this field in 1959: the Committee on the Peaceful Uses of Outer Space (COPUOS). COPOUOS promotes international cooperation in the peaceful uses of outer space. COPOUS also develops legal frameworks to address problems arising from the exploration and use of outer space.

Table 9-1 Outer Space Treaty Related Considerations for SPS

Outer Space Treaty Requirement	Implications for SPS R&D / Operations
All space activities must be carried out for the benefit and in the interests of all countries and shall be the province of all mankind.	This implies that SSP development and SPS system operations must have the potential to benefit all countries.
Space must be free for exploration and use by all countries, without discrimination of any kind.	In general then, SSP development and SPS operations cannot restrict access to space for other space-faring countries.
No country may "appropriate" (i.e., claim possession of) space by any means.	The capture of solar energy in space would not be considered as "appropriation." However, the long-term placement of SPS in GEO slots might very well be considered as a de facto appropriation, and hence must be coordinated internationally.
A country must carry out any space activities in the interest of maintaining international peace and security, and promoting international co-operation and understanding (i.e., conflicts must be avoided).	Early attention to international cooperation in SSP R&D and SPS development should address this requirement.
Countries are prohibited from placing in space nuclear weapons or other weapons of mass destruction.	Future SPS systems must be developed so as to be incapable of being "weaponized". As discussed in Chapter 4, SPS concepts that can be used as weapons cannot be deployed without violating the treaty.
Counties are responsible to the international community for space activities of their public entities and private companies; and, countries are internationally liable for damage caused by the space objects of its public entities or private companies to a foreign state or to its persons.	This implies that commercial space firms pursuing SSP activities will be required to secure appropriate licenses from their respective governments. Future SSP technology R&D and later SPS deployment and operations must be pursued with careful consideration of liability issues (which will depend on whether possible damages are on Earth or in space).
Each country (including private companies within a country) must carry out space activities with due regard to the corresponding interests of all other countries, and avoid harmful contamination of outer space and celestial bodies and also adverse changes in the environment of Earth.	Future SSP technology R&D and later SPS deployment and operations must be planned in accordance with this principal. This will have particular relevance to issues associated with space debris, possible out-gassing from systems in GEO, etc.

During the past 50-plus years, COPUOS has orchestrated several major international treaties and a series of legal principles governing outer space activities. Future coordination of SPS development, and deployment will almost certainly involve this organization.[4, 5]

Beyond the general goal and obligations of international cooperation relating to space activities, there are a number of other important elements of the international legal regime that will constrain and drive SPS development and operations; these are discussed in the paragraphs that follow.

Spectrum Allocation

Naturally enough, the issues of spectrum allocation and management for an SPS system are crucial from the standpoint of international policy and regulations. As many have experienced personally, when two transmissions try to use the same radio frequency, interference ensues. (For example, when driving, the signal from one radio station fades and another grows – both at the same frequency, but physically separated to avoid interference.) Solar Power Satellite related spectrum considerations fall into three broad categories: (a) WPT transmitter spectrum management; (b) WPT receiver emissions; and (c) SPS operational RF emissions.[6]

WPT Transmitter Spectrum Management. The primary challenge in spectrum management for SPS WPT is that of the extremely high power emissions of the transmitter in space. Most WPT R&D has focused on the Industrial, Scientific, and Medical (ISM) RF bands – narrow segments of the electromagnetic (EM) spectrum reserved by international regulatory agreement for use in ISM applications. Clearly, whatever portion of the electromagnetic (EM) spectrum to be employed by an operational SPS, it must be set aside from other communications or operational applications. A WPT system must also be very "clean" – i.e., the energy of the transmission cannot be smeared over a broad range of frequencies, but must instead be restricted to a tight band. Fortunately, solid-state WPT radio frequency (RF) amplifiers of the sort assumed for SPS-ALPHA should be fully capable of accomplishing this requirement.

WPT Receiver Emissions (including Harmonics). There are two principal types of expected RF emissions from the receiving site for an SPS using microwave WPT: the pilot signal (for a retro-directive system) and re-emitted harmonics from the incoming power transmission.[7]

Fortunately, both of these issues should be manageable. The pilot signal can be set to a specific wavelength and generated in a tight band. Re-emission of the received power transmission can be attenuated by including appropriate RF filters in each antenna element of the receiver, as WPT pioneer Bill Brown – whom we met in Chapter 3 – discovered in the 1970s.

SPS Operational RF Emissions. Finally, the ongoing operations of an SPS platform – each of which will be a huge complex of constantly communicating systems – will represent a significant source of RF energy. For example, an SPS of 100,000 modules, each transmitting at a power output of 10 watts, would radiate at 1 MW (50-times more than the most powerful GEO communications satellite in operation circa 2013). Fortunately, the wireless module-to-module communications on-board an SPS-ALPHA platform will be entirely "incoherent" (per our discussion in Chapter 4), and not directed toward any particular spot. Still, the RF wavelength to be used must be chosen with care. For example, these and other SPS RF emissions might interfere with radio science investigations (in which radio dishes on Earth are used as telescopes to study RF emitting objects in deep space). This risk can be minimized with care and coordination.

Spectrum management is a significant issue for future SPS R&D and deployment. However, it should be tractable, depending on early and ongoing coordination through existing national and international organizations, such as the International Telecommunications Unit (ITU). Future R&D activities should formally incorporate a funding consideration of spectrum management issues, including working through various appropriate national and international organizations to assure that knowledge of the potential WPT application and results of studies are well-understood. The constitution and regulations of the ITU apply to radio frequencies for non-communication purposes. Access to and use of portions of the RF spectrum, as well as slots in a GEO, are available on a 'first-come, first-served' basis; most are already taken. Later users (such as SPS) must coordinate with earlier users, and earlier users are under no obligation to accommodate late arrivals.[8] Early SSP research and development efforts and later SPS operations will necessarily require coordination through, and registration with, the ITU. It may be possible – perhaps necessary – for a specific RF frequency to be selected for SPS wireless power transmission (for example, 2.45000 GHz); the selected frequency may well need to be made exclusive. At any event, there is a clear need for technical standards to avoid harmful interference and adverse impact on other systems in space or on Earth.

Orbital Debris Considerations

Orbital debris is a space policy issue that has increased in importance dramatically since the 1970s.[9] The principal location in which orbital debris is found is low Earth orbit (LEO) – due largely to Earth-to-orbit (ETO) transportation-derived fragments and occasional high velocity collisions between spacecraft or smaller objects. There are three aspects to this issue of importance for SPS. First, there is the potential impact of LEO debris on dedicated SPS infrastructure in low Earth orbit: impacts from debris could significantly damage SPS related systems. Another issue is the potential for contributions to the debris in low Earth orbit as a result of the operation of SPS Earth-to-orbit and in-space transportation. Finally, there is the potential for geostationary Earth orbit (GEO) based SPS to contribute to the creation of significant amounts of debris in GEO.

In September 2012, two experts on this subject – Darren McKnight and Donald Kessler – argued that the space-faring nations have already passed a critical "tipping point" with regard to orbital debris in LEO and that without active steps to mitigate the existing debris population future collisions will generate more and more debris.[10] If this argument proves to be correct, the result will be a self-perpetuating cycle in which the amount of debris population grows uncontrollably.

The existing debris in low Earth orbit – not to mention the projected future dramatic increases in debris – places real constraints on any concept of operations for (CONOPS) for future SPS infrastructures. It is evident that the piece-parts of future SPS cannot spend more than a limited period of time in LEO before being transported to higher, safer orbits. Moreover, while SPS in LEO will be at some risk due to space debris, it is also critical that the R&D to develop SPS systems concepts (as well as supporting ETO and in-space transportation) avoid solutions that would exacerbate the production of additional debris in LEO. A proactive step that should be considered is designing SPS ETO and in-space systems so that they not only avoid creating debris but may even actively remove debris.

Mission risk due to orbital debris is significantly less in GEO than it is in LEO. However, given the immense scale of possible SPS operations in or near GEO, it is evident that SPS platforms and infrastructures must be designed and developed to minimize the production of space debris under all but the most extraordinary circumstances. They must operate as a "fail-safe" vis-à-vis space debris in the event of a mishap. In this light, the standard practice of removing a failed GEO satellite by simply boosting it slightly outside of that orbit is clearly unacceptable. SPS in GEO must be developed to incorporate proactive containment and permanent disposition of any failed system elements. The idea that we touched upon in the last Chapter – that of "recycling" failed SPS piece parts – may be an essential strategy in dealing proactively with this issue.

The impact of space debris-related policy and related international agreements on SPS concept options should be manageable if it addressed early and continuously. The greater the degree of modularity in an SPS architecture, the less vulnerable the overall SPS platform will be to an ill-timed space debris impact; conversely, the greater the degree to which the SPS platform is monolithic and its elements unique, the greater the degree of vulnerability of the platform concept to space debris. Although they are non-binding, the International Space Debris Mitigation Guidelines completed by the UN Inter-Agency Space Debris Coordination Committee in 2007 provided generally recognized rules for current and future space operations. SPS efforts will need to take into account the space debris guidelines, including considerations of debris mitigation and the expected debris environment within which an SPS would operate.[11]

Future SPS R&D must explicitly incorporate the challenges of orbital debris, including that related to LEO, GEO and SPS-supporting in-space transportation and infrastructures. The objectives of these studies should include: (a) minimizing SPS systems' vulnerability during ETO, LEO transit, and in-space transportation and operations; (b) ensuring fail-safe operations vis-à-vis the risk of space debris production; and (c) seeking design solutions for SPS supporting infrastructures that could actively mitigate the debris threat. These efforts will need to examine various scenarios, including worst-case scenarios with regard to space debris and Space Solar Power.

Competitive Technology Development Agreements

SSP technology development and SPS deployment and operations will need to be pursued in the context of a tremendous range of national and international policy and regulatory considerations vis-à-vis technology development. It does not appear that these considerations will prevent the future development of SSP; however, they must be carefully examined to assure compliance wherever necessary. Certainly, it is possible that some new international legal structures – such as the International Space Station Treaty – may be needed for specific programs and projects. Moreover, because the objective of SPS development is to ultimately realize commercial power services, the requirements of the World Trade Organization (WTO) must be taken into consideration.[12]

Most advocates in Europe, Japan, and North America expect that Solar Power Satellites will be owned and operated by commercial firms, regulated by governments just as conventional power plants or communications satellite service providers are. Other champions of the concept – China, for example, and perhaps India and other developing economies – may anticipate that future SPS would be owned and operated directly by governments.[13] Regardless of the business model one envisions, WTO rules constrain the amounts and kinds of investment that governments are allowed to make and support during operations provided to firms that compete in international markets. Typically, R&D support is restricted to what is known as "pre-competitive technology" – i.e., developments prior to when a particular firm is developing a specific product for market. (This can include prototypes of various systems.) It is likely that these factors must be considered in framing an SSP technology R&D effort.

Technology Transfer

In addition to international agreements that restrict the types of support governments may provide to technology development, there are also focused, national legal regimes that frame or otherwise constrain the allowable transfer of SSP related technology, and the types of international activities that can be undertaken. For example, the US and other countries impose legal restrictions on the international sale or transfer of technologies that are related to military capabilities including selected space technologies; this collection of rules is known in the US as the "International Trade in Armaments Regulations" (ITAR).[14] Depending on the details of technological choices and international agreements, these restrictions could pose significant barriers to the transfer of technology among government and commercial participants in SSP technology R&D and SPS system development.

A number of countries pursue national policies with respect to specific industries, including the imposition of international technology transfer restrictions. Countries may also formulate specific programs and incentives intended to foster national capabilities in technologies of strategic interest to that country; these can include targeted technology investments, restrictions on eligibility for government contracts, tax and related incentives for investments, and other means. Efforts to pursue SSP must work carefully within the framework for these specific national restrictions.

Insurance and Indemnification for SSP

As with any new industry, there will inevitably be issues for SSP associated with indemnification in the event of an accident and how insurance for this new industry may be provided. For example, as mentioned earlier, the Outer Space Treaty sets international norms vis-à-vis space activities and liability. Looking at the overall CONOPS for SPS-ALPHA presented in Chapter 8, there are a number of opportunities for operational risks – and therefore a potential need for insurance or indemnification. In this regard, there are useful precedents in the "new space" arena involving insurance for public space travel (i.e., "space tourism") and in other sectors, such as in the energy industry, involving nuclear power plants.

Energy Policy

Although very important for SSP, we have not discussed energy policies *per se* at this point; rather, this is a major topic in Chapter 12, which concerns the terrestrial market for Space Solar Power. The most important aspects of energy policy include plans for government investments in energy R&D and other policy-driven sustainable energy incentives, such as feed-in tariffs.

Resolving Legal and Policy Related Issues

Just as R&D is needed to mature key SSP technologies, research is also needed concerning legal and policy-related matters. Fortunately, there are a number of individuals and organizations that have expertise in these matters. One of these is the International Institute of Space Law (IISL), one of the participating organizers of the annual International Astronautical Congress (IAC).[15] The annual meetings at the IAC provide a highly useful opportunity for international experts to explore potential solutions to the legal and policy-related issues vis-à-vis Space Solar Power.

Space Solar Power and the Environment

Even though SPS are technically feasible, and even if they can provide energy at an economically competitive price, the question remains: would SPS be acceptable from the perspective of the environmental community? In other words, would Solar Power Satellites make a net positive contribution in mitigating damage to the environment and the risks of anthropogenic climate change, or would they exacerbate those risks? Several factors must be examined to resolve this question: the energy cost of manufacturing SPS, the energy cost of deploying SPS, and the environmental impact of deploying and operating SPS. In summary: if they are to be of interest in pursuing the goals of sustainable energy policies, SPS must be competitive with other technology options in terms of "greenness."

Let's start by examining the potential environmental impact of SPS construction and launch in comparison to other activities of the global economy.

SPS Fabrication

By its nature, a Solar Power Satellite will be enormous; it must be if it is to harvest enough sunlight to make any difference. However, the same is true for terrestrial solar power systems. In order to represent a peak generating capacity of 2,000 MW (i.e., 2 GW), a ground solar power plant in a good location would have to have an area of roughly 8,333,000 m^2 – representing a circle with a diameter of a bit more than 3,300 meters (a bit more than two miles).[16] Suppose that a given market required 2 GW of continuous (aka, "baseload") power, energy totaling about 48,000,000 kW-hrs daily. Given the day-night cycle, changes in sun-angle due to the seasons, and the effects of weather in most locations on Earth, the ground-based PV array would have to be roughly 4- to 10-times larger to ensure continuous delivery of 2 G – some 30 to 80 square kilometers in area, or about 6 to 10 kilometers in diameter (up to 6 miles). The mass of such a PV array would be on the order of 100,000-200,000 metric tons. The ground-based solar power system would also require a stupendously large energy storage system to provide power at night or on days when skies are overcast. For example, a current-technology lithium-ion battery energy storage system would have a mass of roughly 3,000,000 metric tons in order to provide power for 24 hours (all day, following a full day of cloudy skies).[17]

Together then, a ground-based solar baseload power system to continuously deliver 2 GW would have a total mass of approximately 3,200,000 MT – a truly huge system. All of this is why ground-based solar PV arrays are operated in conjunction with other sources of energy – typically coal or natural gas power plants – and as only a relatively small fraction of the total capacity (e.g., about 10%-20%, at most). In this way, no energy storage systems are required and the PV arrays do not need to be over-sized to cope with overcast days.[18]

The reason to walk through the ground-based solar PV numbers was to establish a basis for comparison with a Solar Power Satellite that would deliver a similar amount of power. In particular, using materials and device technologies that are already proven in the laboratory, the mass of an SPS-ALPHA platform delivering some 2,000 GW would be roughly 20,000-30,000 MT – a tiny fraction of the mass of the comparable ground based system solar PV array. A detailed bottoms-up estimate is needed, comparing specific materials to be used, and so on. However, the basic argument I offer here is simply this: if an SPS-ALPHA delivering 2 GW of baseload power has a mass of less than 10%-20% of the mass of a ground-based PV array of similar capacity, it is likely that the environmental impact of the *fabrication* of the Solar Power Satellite will be much less than that of a similar ground-based PV array. Of course, there is still the mass of the SPS wireless power transmission receiver to consider; however, preliminary estimates suggest that the receiver would have a mass much less than that of a PV array of similar area. Comparing the WPT receiver to the energy storage system required for the ground PV array suggests again that the fabrication of the receiver will have far less impact that that of the energy storage system. In summary, to meet demand for 2 GW of baseload power, it appears that the *fabrication* of an SPS-ALPHA platform and receiver will have less environmental impact than the fabrication of a similar ground-based PV array with energy storage system – with a total mass of about 100,000 MT-200,000 MT versus more than 3,200,000 MT, respectively.

Next: what about the environmental impact of deploying the SPS-ALPHA to its operational orbit?

SPS Launch

In the case of a Solar Power Satellite with a total mass of 20,000 metric tons (MT) – i.e., approximately 44,000,000 lbs – a fleet of reusable ETO vehicles with a "per vehicle" capacity of 20-25 tons to LEO would have to make roughly 1,700 flights to launch both the platform pieces and the propellant to move those parts to GEO. Clearly, the reliability of the reusable launch vehicle (RLV) will be of great importance to those at the launch site and downrange from it; so will the path of the RLV during reentry and return to prepare for the next flight. The means of launch – such as the choice of propellants – could have unintended impacts on the atmosphere, including the extreme upper atmosphere (e.g., the ionosphere).[19]

The specifics of environmental interactions can be determined only once the details of an SPS launch system are known. However, by way of comparison, let's take a moment and examine the closest existing analog to SPS launch: commercial air transportation. What are the numbers? Commercial air transportation is a tremendous industry; a single major airfreight firm might handle as much as 10,000 MT of freight through a single airfield every day.[20] This is roughly equivalent to the hardware mass of a full-scale, 2GW Solar Power Satellite every two days. Hence, such an airfreight firm handles shipping each week equivalent to about two SPS (including propellant for transportation), or more than 100 SPS per year. Clearly, in the context of the global economy, the ground-based aspects of SPS deployment or logistics should have no significant environmental impact.

What about the emissions into the atmosphere? The international airfreight and air travel industries consume approximately 210,000 liters (about 56,000 gallons) of jet fuel per day, or about 20.4 million gallons per year (in other words, roughly 76.5 Million liters per year, with a total mass of about 92,000 MT/year [21]). The exhaust to the atmosphere from the global jet transport industry therefore totals something like 245,000 MT per year, comprising primarily carbon dioxide and water as well as some carbon monoxide and other trace chemicals. Adding in commercial passenger air traffic and military flights, the total aviation sector produces exhaust to the atmosphere of about 1,000,000 MT per year. By comparison, a hypothetical single-stage-to-orbit (SSTO) reusable launch vehicle (RLV) using liquid oxygen (LOx) and liquid hydrogen (LH_2) propellants would produce about 800-900 MT of exhaust (almost entirely water vapor, H_2O) to launch 25 MT to LEO.[22] Placing a mass of about 20,000 MT in LEO with such a vehicle would therefore require approximately 1,000 launches and produce an exhaust to the atmosphere of roughly 1,000,000 MT; a significant amount, certainly, but also potentially almost entirely water vapor.

Let's look at this another way: how would emissions due to SPS ETO transportation compare to emissions from the global economy? Each barrel of oil contains about 140 kg of oil and, after combustion, results in approximately 300 kg of exhaust to the atmosphere, comprising CO_2, H_2O, CO, and trace gasses). The global economy (including air transport) consumes at present (2013) about 90 million barrels per day (or some 13,000,000,000 kg daily), and after combustion corresponds with a total exhaust to the atmosphere of about 10,000 million MT per year.[23] By way of comparison, the global economy's consumption of petroleum results in emissions per year 10,000-times greater than the launch of a full-scale SPS.

To summarize, the emissions into the atmosphere that would result from launching an SPS aren't trivial, but neither are they overwhelming – particularly if the propellants are LOx and LH_2 and the exhaust may be primarily water vapor. This topic will require careful attention during future R&D efforts.

One more thing. Of course, the best "launch" solution from the perspective of atmospheric interactions would be no launch at all – in other words, fabricate the SPS platform entirely from extraterrestrial materials. (This topic was touched on in Chapter 8.) Although this is an interesting option for the longer term, it is not the way to get started. If SPS require space resources before they can be built, then we must wait until those resources are available to do anything on SPS. However in the absence of massive government funding, how can the development of space resources be financed unless there is a market into which to sell them? Although initial progress could be made quickly, the large-scale commercial development of space resources will require many years and the emergence of numerous new technologies and systems. In the meantime, initial development of commercial SPS would provide a terrific market for those resources.

One more topic is frequently raised vis-à-vis the "greenness" of new energy systems: the energy investment payback time. Let's discuss this next.

Energy Investment Payback

A key figure of merit for sustainable energy systems is how quickly the energy required to fabricate and deploy the system can be delivered after it begins operations; this is known as the "energy payback time." Ground-based solar power PV systems that are not required to provide stand-alone baseload power can achieve energy payback in 1-5 years for all types of solar arrays, including various cell technologies and system deployment schemes (ranging from building integrated PV (BIPV) to large-scale centralized PV-based power plants). A major driver of this payback time is the physical location of the PV power plant with desert locations (e.g., the Southwestern US) providing much faster payback than northern latitudes.[24] It appears that times for energy payback for large PV solar power plants are in the range of 1-3 years.

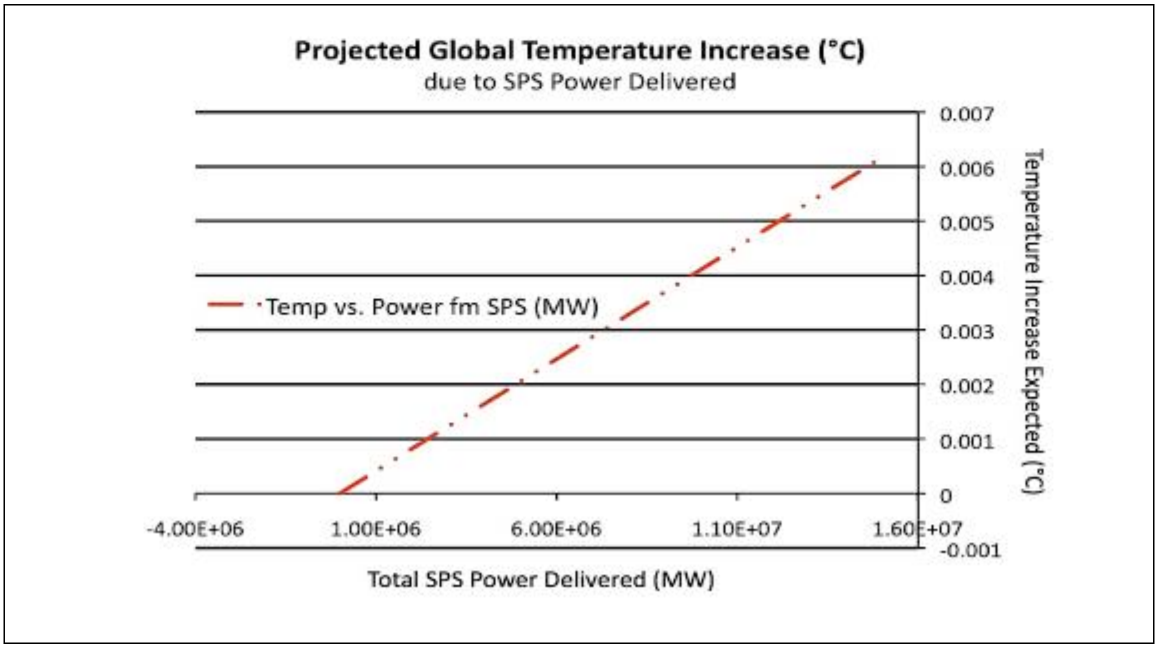
By comparison, recent studies comparing ground solar power and space solar power (per 2002-2004 European Space Agency SPS studies) suggest that large-scale space solar or ground solar power plants might achieve energy payback in one year or less (although this estimate is highly dependent on various assumptions).[25] As was done in the case of the recent ESA studies, future systems analysis involving commercial "baseload power," must make distinctions among SSP and other energy options, including consideration of any needed over-sizing of renewable power sources, and the addition of energy storage systems. However, after an initial consideration, the energy payback time for SPS appears perfectly competitive with ground solar.

What About Heating the Earth?

So, it appears that Space Solar Power would in principle provide an extremely "green" (i.e., sustainable) energy alternative for the future. However, SPS would certainly intercept sunlight that would otherwise bypass Earth, and redirect that energy into the environment. Do we need to be concerned that this added energy will heat the Earth? The simple answer is, "no."

During the recent IAA study, a preliminary analysis was performed to determine the expected heating that might be expected due to a Solar Power Satellite beaming energy to Earth that would otherwise have passed without interception in nearby space.[26] Figure 9-1 presents the results of this high-level calculation of the total increase in the Earth's temperature that might be expected to result from the use of SPS to deliver a substantial share of the energy needed to drive civilization – about 15,000 GW.

Figure 9-1 Calculated SPS Contribution to Earth's Temperature



Credit : Artemis Innovation Management Solutions (2013)

From this analysis, it appears that a single SPS that delivered about 1.5 GW of power would add less than 0.000001 °C to Earth's average temperature. By extrapolation, it appears that several thousand SPS with a total delivered power of about 15,000 GW (equivalent to the total global consumption of power circa 2005-2010) would result in less than 0.006 °C increase to Earth's temperature – an extremely tiny amount compared to the aggregate thermal effects of similar power production from fossil fuels. It seems evident from this first-order calculation at least) that the heating effect of many more SPS (above the current total world energy consumption) would still result in a quite small increase in Earth's average temperature.

So, would SPS-ALPHA be a "green energy" solution? At present, it appears that Space Solar Power could be a highly "green" option, with minimal energy cost for SPS space transportation, good energy payback times compared to centralized ground PV solar power plants, and extremely small contributions to increasing Earth's temperature. More detailed studies are needed, of course, including integrated input-output matrix studies in order to better understand the true energy investments needed for SPS, and the resulting energy payback times that are required for these systems.

There is one more topic that we must still consider: would WPT operations be safe?

Wireless Power Transmission Health and Safety

Often, proposals to use WPT cause some to voice concerns about power transmission safety. This concern has been expressed in a tongue-in-cheek fashion by WPT pioneer Richard (Dick) Dickinson of NASA's Jet Propulsion Laboratory as the "fear of frying," indulging in a bit of word-play on the phrase "fear of flying."

As discussed, there are several alternative approaches that might be taken to perform wireless power transmission from an SPS to the ground, including microwaves, lasers, and millimeter waves. The performance related pros and cons of various WPT options were further discussed in Chapter 4; the upshot is that the two primary options are microwave and lasers, and of these the microwave transmission option offers the best potential for economically viable SSP at larger scales.

Over the past several decades, there have been a number of research studies on the effects of microwaves on various flora and fauna. For example, bees were exposed to microwave energy as part of NASA-DOE SPS research studies in the 1970s. Figure 9-2 is a photograph of numerically tagged bees from these studies.

Figure 9-2 Numbered Bees in Microwave Tests in the 1970s

Image Courtesy NASA

Similarly, in Japan, a “microwave garden” was developed during the past 15 years within which various species were exposed to low intensity microwave energy and monitored over time; no negative effects have been reported from these studies. Also, in the late 1990s, further studies were done by Dr. Jay Skiles of the NASA Ames Research Center as part of the SSP Exploratory Research and Technology (SERT) program. The studies examined the effects of low-level microwave exposure in alfalfa. No effects – and in particular no mutagenic effects on the plants’ DNA – were observed in these studies.

In order to assure beam safety, the ground rule recommended by the International Academy of Astronautics (IAA) in its 2008-2011 study of Space Solar Power was that the maximum allowable energy intensity in a wireless power transmission should be less than the intensity of full summer sunlight at the equator – in other words, less than 1,000 watts per m^2.[27]

Potential for Weaponization

The principal source of concern vis-à-vis potential weaponization is related to SPS wireless power transmission. In the 1970s, there was little or no issue associated with the weaponization of SPS platforms for several reasons. For example, the 1979 SPS Reference System involved a low intensity microwave power transmission system. Moreover, the beam was incapable of being rapidly redirected due to the use of a huge mechanical gimbaled system for large angle point. All of the systems in the ERDA-NASA studies of the late 1970s were to be positioned over the equator at the longitude of the US, which was the only market to be served.

However, some of the SPS concepts considered by the IAA study would be capable of being rapidly redirected, or in some cases higher beam intensities were considered (particularly for laser WPT concepts). As a result, two principal weaponization issues were considered: (a) those concerning terrestrial risks and (b) those concerning objects in space. The following discussion treats these in turn. (We talked about these issues in Chapter 4.)

A key issue vis-à-vis the potential weaponization of a future SPS with respect to objects on Earth involves the temperature of objects on the Earth that are illuminated by the WPT transmission. In particular, the concern is associated with the possible use of the SPS transmission to ignite targets on Earth. A preliminary analysis of this problem was conducted as a part of the recent IAA assessment, which incorporated four main ideas:[28, 29]

(1) The maximum temperature of an illuminated surface will reflect equilibrium between the energy input to the surface and the energy output from the surface (for passively cooled objects).

(2) The key component of energy input is radiant energy incident on a surface as a blackbody (this is a simplifying assumption).

(3) The output energy from a surface will be approximately the sum of the convective cooling of the surface and the radiant energy from the surface as a blackbody (this is another simplifying assumption).

(4) The upper temperature limit allowable is that at which an illuminated wood, paper, or a similar surface material would ignite.

The principle observation of the analysis was that at night (i.e., with no incident sunlight), the allowable incident WPT intensity at Earth is not more than approximately 6,000 W/m^2 – corresponding to a temperature of about 505 Kelvin (i.e., 451°F – the standard combustion point of paper and/or wood). During the daytime, the solar flux must be added to the WPT beam, and the total should be less than this upper limit for incident intensity; for local noon during the summer, the upper limit appears to clearly be about 5,000 W/m^2 (which again corresponds to the combustion point of paper / wood).

In addition to the risks of combustion, even at lower intensities there can be risks, depending on the choice of technology. The greatest danger that might occur from SSP comes from the choice of a laser for wireless power transmission. As is now well known, eye safety cannot be neglected: even low levels of laser light can cause permanent damage to the retinas of humans and animals. It seems likely to me that only microwave power transmission – at low levels of intensity and zero risk of ocular damage – will ever be acceptable.

There is one further consideration vis-à-vis potential weaponization: the issue of possible threats to in-space objects. In this case, there are a wide range of issues, including possible illumination and damage to sensors systems, possible damage to on-board power systems, and potential to induce damaging charging and electrostatic discharges. These issues are highly sensitive to the choice of either RF or laser WPT, as well as specific power levels. In general, however, the key capability involves rapid, precision and independent pointing of high intensity WPT transmissions.

As is true for almost all energy sources, there are potential risks of weaponization of SPS technologies and systems involving either terrestrial or in-space targets. In the case of the former, the biggest issue involves possible risks to eye safety for laser wireless power transmission at visible or near-visible wavelengths that are capable of passing through Earth's atmosphere. For structures or systems that might be illuminated by a WPT transmission, the physics of heat transfer vis-à-vis objects on Earth sets a clear upper limit for the peak energy intensity that an SPS WPT system should be allowed to deliver to Earth. However, there is the additional issue of how easy (or difficult) it will be for multiple SPS to combine their transmissions on a single target. For the sake of assured safety in SPS/WPT operations, it seems clear that both additional R&D and specific system design steps will be needed.

In the case of microwave WPT, an upper limit of about 200-250 watts per m^2 was assumed in studies of the 1970s. A similar upper limit seems entirely appropriate for near visible laser WPT as well. This limit would ensure that even in the case where the WPT transmissions from 18-20 SPS were simultaneously directed at the same location on Earth, the energy intensity necessary for weaponization limit would not be exceeded.[30] In any event, this is clearly a topic that must be considered in greater detail, and with great public transparency in future SSP R&D efforts.

Summary Observations

There are policy and regulatory issues that must be addressed as SPS related R&D goes forward. These range from international technology transfer concerns to spectrum management, but do not appear to present contain any showstoppers for SPS. However, care must be taken to resolve these issues in close tandem with future technology maturation efforts.

As we have seen, Space Solar Power would be a “green” energy solution, producing far less environmental impact in fabrication than other sustainable energy options and achieving energy payback in reasonable timeframes. SPS would not raise global temperatures to any significant extent compared to global emissions from power generation and transportation. Nevertheless, care must be taken to ensure that these issues are well understood and addressed.

All sources of energy – coal, oil, natural gas, nuclear power, hydro-power, wind, and so on – involve advantages and risks; Space Solar Power would be no different. For example, the hazards of coal use for electricity production resulted annually in some 170,000 deaths per Trillion kilowatt-hours in statistics through 2012 (primarily due to air pollution, but also mining accidents).[31] Detailing and resolving Space Solar Power challenges related to health, safety and the environment will require action on several fronts and must be pursued when a major SSP effort is next advanced. All-in-all, fundamental design choices must be made in the context of these issues in order to mitigate and eliminate where possible any hazards.

Moreover, existing sources of energy – particularly petroleum – are obviously used in weapons systems. In order to ensure that the risk of weaponization for SSP is minimized, its seems clear that the peak power intensity delivered by a single SPS platform must be substantially less that the intensity at which ignition of common materials could be caused. In addition, no easy combination of power transmission from multiple SPS platforms should be sufficient to exceed safe limits vis-à-vis combustion. And, as we’ve noted, it is now clear that even low levels of laser light can cause irreparable harm to retinas – in humans and other animals.

So, in the past four Chapters, we have examined each of the major hurdles for SSP: the cost of hardware; the costs of space transportation; the need for transformational in-space operations; and finally, the policy, safety, and environmental concerns that must be considered. In each case, there are real challenges, but no showstoppers. Space Solar Power is doable; the next question must be: is it worth the doing? That will be the subject of the next major section of this discussion.

[9-1] See: http://en.wikipedia.org/wiki/Dionysius_Lardner. There is a much more famous misquotation attributed to Martin Van Buren, writing to President Andrew Jackson around January 1829 (before Jackson had even been sworn in as President!) Van Buren's supposed letter has been thoroughly debunked. The statement above, attributed to Lardner is evidently one that the Irish scientific writer actually made.

[9-2] In addition, Appendix C provides a snapshot of a number of the "but what about…?" questions that are often posed regarding Space Solar Power – along with answers.

[9-3] See: http://en.wikipedia.org/wiki/Intelsat and http://en.wikipedia.org/wiki/COMSAT.

[9-4] For further information, see: http://www.oosa.unvienna.org/oosa/COPUOS/cop_overview.html.

[9-5] See: http://www.unoosa.org/oosa/SpaceLaw/outerspt.html. Also, see this topic in the International Academy of Astronautics "First International Assessment of Space Solar Power" (IAA). 2011.

[9-6] We have already discussed the efforts of Prof. Kozo Hashimoto in laying out spectrum related issues for SPS; see Chapter 3.

[9-7] When a "rectenna" receives an RF transmission, most of the electromagnetic energy is converted into electricity. A small portion, however, is re-radiated (a bit like a faint reflection from an almost clear pane of glass). These "harmonics" – as the retransmission is called – are small, and occur at specific frequencies that are multiples of the original transmission. In other words, if the WPT transmission is at a frequency of 2.45 GHz, then the harmonics will be at 4.9 GHz, 9.8 GHz, etc.

[9-8] This is, by the way, a powerful argument for exploring the placement of SPS in orbits near GEO, but where the platforms are not in GEO.

[9-9] For a good overview of this important subject, see NASA's website: http://orbitaldebris.jsc.nasa.gov/

[9-10] McKnight, D. and Kessler D.D.; "We've Already Passed the Tipping Point for Orbital Debris" (Opinion in *IEEE Spectrum*; see: http://spectrum.ieee.org/aerospace/satellites/weve-already-passed-the-tipping-point-for-orbital-debris). September 2012.

[9-11] See: http://www.iadc-online.org/index.cgi?item=docs_pub

[9-12] See: http://www.wto.org

[9-13] Of course, most policy makers have no knowledge of Space Solar Power or Solar Power Satellites, and as a result have no opinion on the matter!

[9-14] See: http://en.wikipedia.org/wiki/International_Traffic_in_Arms_Regulations

[9-15] See: http://www.iislweb.org/

[9-16] This rough analysis assumes (1) a PV array efficiency of 30%, and a specific mass of about 25 watts per kilogram; (2) that not more than 50% spacing is required around the solar arrays so that they don't shadow one another in the morning and afternoon; and (3) that there are at most 1-3 days of overcast weather at a time. The last number is not very realistic for most of Earth's populated regions where bad weather can last one or more weeks at a time.

[9-17] See: https://en.wikipedia.org/wiki/Lithium-ion_battery.

[9-18] In recent years, interest has increased in Concentrator Solar Power (CSP) involving molten salts for energy transfer, which inherently provide several hours of power generation after the sun has begun to set in the afternoon. These and related systems involving solar-thermochemical energy storage appear promising for reducing the cost of ground-based solar energy storage.

[9-19] Of course, any ambitious and large-scale future space activities that require frequent launches – such as public space travel – must work through these questions.

[9-20] For example, FEDEX Field in Memphis, Tennessee.

[9-21] See: http://flyunleaded.com/Aviation_Fuel_Update_6_2012.pdf

[9-22] This is NOT a book about space launch systems; however, it is impossible to talk about Solar Power Satellites without discussing access to space. The numbers presented here (and elsewhere in the text) are rough estimates only; please take them with a grain or two of salt…!

[9-23] See: http://omrpublic.iea.org/

[9-24] Pearce, J. and Lau A., “Net Energy Analysis for Sustainable Energy Production from Silicon Based Solar Cells,” (Proceedings of Solar 2002 Sunrise on the Reliable Energy Economy, Reno, Nevada). June 15-20, 2002.

[9-25] Franco Ongaro, Leopold Summerer; “Peter Glaser Lecture: Space and a Sustainable 21st Century Energy System”; (57th International Astronautical Congress, Paper IAC-06-C3.1.01). 2006.

[9-26] This analysis used the Stephan-Boltzmann law relating energy emitted to temperature and assumed the Earth was in energy balance, with an estimated total solar flux intercepted by Earth of $1.746 * 10^{17}$ watts, a nominal average terrestrial temperature of 15° Celsius and an estimated average emissivity for Earth of 0.8875.

[9-27] This recommendation did not explicitly take into account the question of eye safety in the event laser WPT is being considered.

[9-28] Personal communication with Robert Wegeng (February 19, 2010).

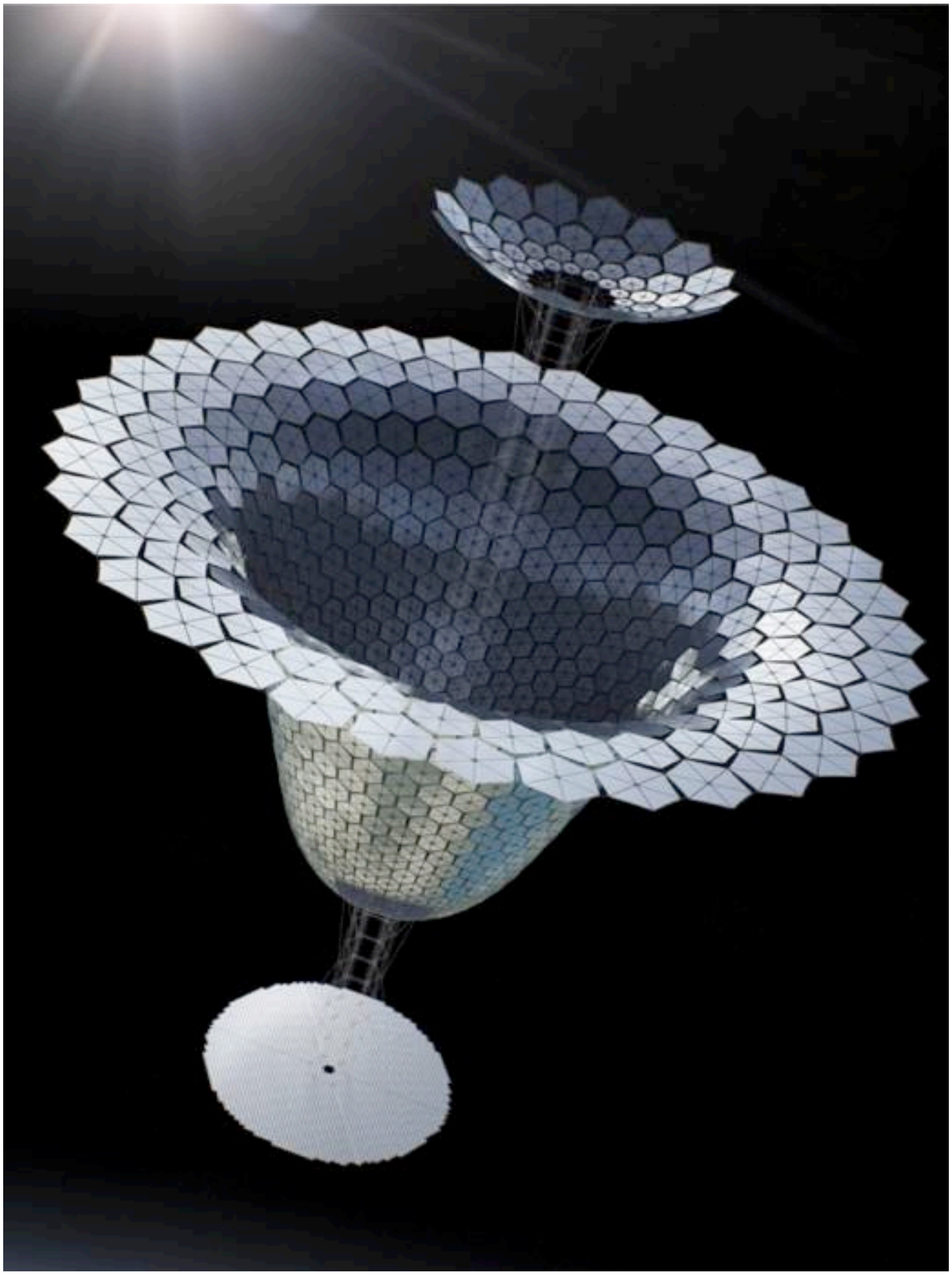
[9-29] A number of considerations were dropped from the IAA analysis for the sake of simplicity; for example, the fact that energy is radiated from all surfaces of an object, not just the surface illuminated by the WPT beam. A more detailed analysis is needed.

[9-30] Through the use of “fail-safe” design approaches (e.g., involving the pilot signal) with a retro-directive phased array WPT transmitter, it should be possible to provide even greater assurance that weaponization of SPS transmissions cannot occur.

[9-31] See: http://www.forbes.com/sites/jamesconca/2012/06/10/energys-deathprint-a-price-always-paid/

Part IV

Opportunities



Chapter 10
SPS-ALPHA Design Reference Missions

"One test result is worth one thousand expert opinions."
Wernher von Braun
While at the NASA Marshall Space Flight Center

Introduction

The concept of the "Design Reference Mission" (DRM) is one that I first learned at NASA in the context of planning for future Human Space Flight (HSF) missions. The first time was when DRMs were used as a tool in translating mission requirements into system specifications during the Space Station program in the 1980s. I saw them used again in the conduct of studies of Human Mars Mission studies in the 1990s. A "DRM" is not intended to be the actual solution, although sometimes it is mistaken for one. It is supposed to address the functional requirements a mission designer is trying to satisfy. Also, a DRM should "close" – meaning that it should be internally consistent and doable in terms of known physical constraints and engineering interfaces. A good DRM provides useful insights into where tough design choices lie waiting, and what technology advances may be needed.

The 2011-2012 NIAC-sponsored Phase 1 study produced preliminary definitions of the SPS-ALPHA concept for several distinct Design Reference Missions (focusing on the platform). These DRMs will be used as a foundation for the discussions in subsequent Chapters concerning missions and markets, the integrated business case, and later as the building blocks for the proposed implementation roadmap for SPS-ALPHA.

The purpose of this Chapter is to describe these Design Reference Missions in some detail. The Chapter also presents the results of a systems analysis focusing on the details of the DRMs, including the numbers of each type of module, the masses of each type, and a preliminary cost estimate for each of them.

One More Thing ... Sensitivity Studies

In any systems analysis, assumptions must be made concerning the expected characteristics of various technologies and subsystems. For example, the "specific power" of a solar array (i.e., watts per kilogram) affects the overall mass of the platform. Similarly, the efficiency of the WPT system (RF-watts-out versus electrical-watts-in) determines the required size of the solar power generation system, and so on. There are an almost infinite number of sensitivity studies that might be conducted concerning the various Figures of Merit (FOMs) for the technologies used in the different SPS-ALPHA DRMs. Table 10-1 below highlights some of the parameters that were considered in the Phase 1 systems analysis.

Table 10-1 SPS-ALPHA System Analysis Figures of Merit

Architecture-Level Figures of Merit (FOMs)	Selected System-Level FOMs	Selected Technology-Level FOMs	Selected Modeling Outputs
Power Delivered at Earth (MW)	Time Between Refueling Operations (yr)	Material Density, by Material (kg/m3)	Number of Modules, by Type (No.)
Orbital Altitude (km)	Reflector Type (Shape)	Solar Power Generation Specific Power (kW/kg))	Mass of Modules, by Type (kg)
WPT Transmission Frequency (GHz)	Primary Structure Assembly Diameter (m)	Selected Module Specific Mass (e.g., kg/m2, kg/m, etc.)	Station-Keeping Propellant Mass Required (kg)
Fractional Expendability (HW % Expended per Yr)	Primary Array Assembly Diameter (m)	Average DC-RF Device Power (W-output/Device)	Specific Cost of Hardware, by Module Type ($/kg)
Discount Rate (%/year)	Receiver Diameter (m)	WPT-Transmitter DC-RF Conversion Efficiency (%)	Specific Power per Device
Manufacturing/Learning Curve (%/Doubling)	Technology Selections (e.g., SPG, WPT, etc.)	WPT-Receiver RF-DC Conversion Efficiency (%)	Concentration Ratio
Price of Electricity, by Market ($/kW-hr)	Structural Systems Approach(es)	Various Detailed FOMS	Levelized Cost of Electricity (LCOE; $/kW-hr)

Given the constraints of time and resources, the recently completed study included only a handful of sensitivity studies. These were chosen to illuminate the importance (or lack thereof) of specific technology areas in the SPS-ALPHA system; the areas explored were: (1) structural mass and materials; (2) DC-RF conversion efficiency in the WPT system; (3) WPT mass per unit area; and (4) variations in the concentration ratio for the system that would be enabled by changes in device materials choices.[1] The majority of the sensitivity studies were performed on the fully commercial, recurring SPS-ALPHA case described as "DRM-5" that would deliver 2 GW power to terrestrial markets.

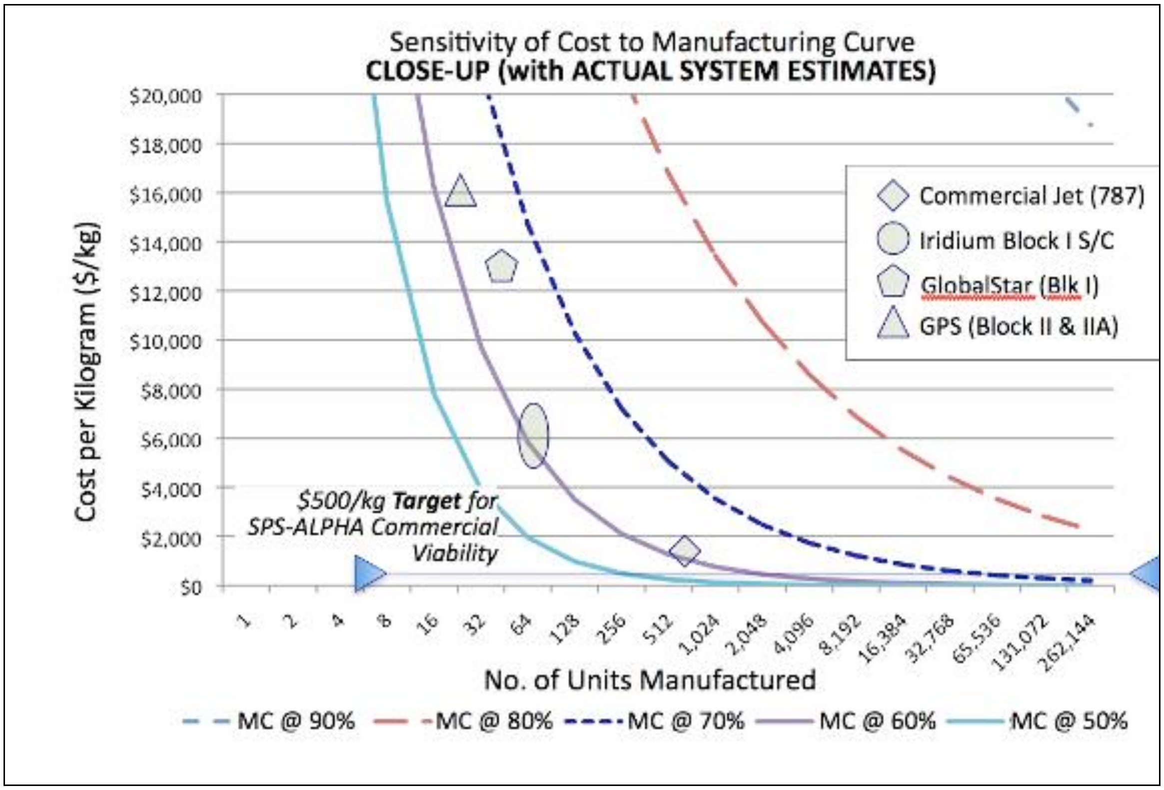
And Another ... Cost Estimation

A preliminary market forecast was developed and analyzed as a part of the SPS-ALPHA NIAC Phase 1 project, focusing on commercial terrestrial baseload energy markets for the Solar Power Satellite. It also included ancillary markets such as secondary terrestrial power markets as well as prospective space applications of the SPS-ALPHA architecture, systems, and technologies. These results have been updated for the present volume and are presented in Chapters 11 and 12; they are integrated into a unified business case for Space Solar Power in Chapter 13. However, it is impossible to evaluate the economic potential of SPS – or any new system or product – without considering costs as well as markets. Five major system cost components have been identified: (1) hardware manufacturing costs (including both initial hardware and replacement parts over the lifetime of the platform); (2) Earth-to-orbit transportation cost; (3) in-space transportation cost; (4) ground receiver cost; and (5) operations and maintenance (O&M) costs.

Manufactured Hardware Cost Estimation. In Chapter 6, we discussed at length the issue of the high costs for space hardware and the basic strategy of the SPS-ALPHA architecture: a modular and networked approach with low cost achieved through large-scale production. The SPS-ALPHA hardware cost estimates discussed in this Chapter were developed using a mass-based cost estimated relationship (CER) approach at the module level, with the application of a learning curve / manufacturing curve (LC/MC).[2] Figure 10-1 illustrates several aerospace systems examples, plotting historical data for the unit production quantity and the cost per kilogram CER.

For the cases shown – ranging from Global Position System (GPS) satellites to a commercial jet aircraft similar to the Boeing 787 – the experience curve (LC/MC) falls roughly between the values of 60% and 70%. On this basis, the NIAC study assumed an LC/MC of about 66% for SPS-ALPHA module cost estimation; that value underlies the results presented in this Chapter.

Figure 10-1 Selected Aerospace Examples in the Context of Learning Curves



To infer the LC/MC values in Figure 10-1, the assumption was made that the initial CER for all systems was $250,000 per kilogram. If the initial CER is greater, then the true LC/MC must be even better (i.e., lower) than about 60% for the cost per kilogram observed; alternatively, if the initial CER is lower, then the LC/MC may be somewhat greater than 60%. Also, it is interesting to note that the observed LC/MC value for the commercial aircraft case is a bit greater than 60% as compared to the first documented case of the LC/MC in the literature (Wright's 1936 paper, previously cited), which documented a "progress curve" of some 80%, which involved manufacturing without automation.

The detailed hardware cost estimation results for each of the several Design Reference Missions are presented in tables on the pages that follow. The primary emphasis in the detailed cost estimation has been on the manufactured hardware costs, as we've discussed. The other cost components, described below, were treated only at a very high level.

Space Transportation Cost Estimates. As we discussed in Chapter 7, the two major components of space transportation costs – ETO transport and in-space transport – are in themselves each topics requiring detailed study. In line with the resources available for the NIAC Phase 1 study, only a very superficial set of CERs was assumed for space transportation cost estimates. These CER sets were based on recent publicly announced launch prices (for the nearer-term case), and on the result of NASA's HRST study of the 1990s (for farther-term cases) (see Chapter 7). These are summarized in Table 10-2, below.

Table 10-2 Space Transportation Cost Estimation Relationships

	ETO Transportation ($/kg)	In-Space Transportation ($/kg)
SPS-ALPHA Technology Demos in LEO	$3,500 / kg	N/A
SPS-ALPHA Pilot Plant Demos in GEO	$1,500 / kg	$1,500 / kg
Full-Scale SPS-ALPHA in GEO	$ 500 / kg	$ 500 / kg

A central feature of reusable transportation systems of all sorts is that the cost per use drops with increasing traffic; i.e., the greater the number of vehicles manufactured and the greater the use of each vehicle, the lower the amortized share of fixed costs for each payload. This feature is reflected in Table 10-2: as the scale increases, so do the number of launches, and the cost per kg to LEO is assumed to decrease commensurately. It is implicit in the ETO CER of $500/kg that a Reusable Launch Vehicle (RLV) must be employed for SPS hardware deployment and logistics. Also, for the in-space transportation CERs, the underlying assumptions are that the transportation system is reusable and highly fuel-efficient (e.g., solar electric propulsion), such that the ETO cost of the fuel to be used essentially sets the cost of in-space transportation.

Ground Receiver Cost Estimates. In the SPS-ALPHA NIAC study, the costs of the ground-based WPT Receiver for the SPS cases were estimated based on a simple, area-based, cost-estimation relationship of $10 per m^2. This estimate assumes that the millions of very simple rectifying antenna ("Rectenna") elements to be used in the receiver can be fabricated in a highly automated fashion and at low cost. The resulting contribution of the Receiver to the levelized cost of electricity (LCOE) must, of course, depend on the amount of power transmitted and received.

A general observation should be made at this point: it is unfortunate that the ground Receiver received too little attention in most SPS studies of the past 25 years, all of which have assumed that past results were still valid. In the 1970s, the estimated cost of the Rectenna was on average $1 per watt, where the peak power intensity was approximately 230 W/m^2 at the center of the receiver and the minimum was around 2 W/m^2 at the edge. The average power density was roughly 50 W/m^2 and, in terms of cost per unit area, the 1970s estimate was around \$50/m^2. Given the level of automation in precision electronics manufacture in the 1970s and advances during the past 40-plus years, the current goal of \$10 / m^2 – expressed in the CER – is ambitious, but not unreasonable.

Operations & Maintenance Cost Estimates. Operations and maintenance (O&M) for SPS-ALPHA comprises several major cost components: (1) cost of labor and hardware for pre-planned maintenance replacements; (2) the cost of labor and the cost of hardware required for unexpected spares; and (3) the cost of ongoing operations (e.g., control center type) personnel. The CER for the cost of hardware for spares and replacements on the SPS platform were accounted for as part of the hardware cost estimation, described above, with an estimated annual repair and maintenance requirement of 3% of the overall mass of the platform per year. The costs of ground operations were estimated (very roughly) at 1% per year of the total value of the initially deployed SPS-ALPHA platform hardware. Finally, in addition to the above, a fixed annual program operations cost of \$5M per year was assumed. Note that the O&M costs for ETO and in-space transportation systems and supporting infrastructure are not included here; those costs are incorporated (by assumption) into the mass-based CER for both.

All of the above are topics that require additional definition and more detailed assessment in the context of future Space Solar Power business case analyses. As they stand, however, they are the basis for estimating the Life Cycle Cost (LCC) of each of the SPS-ALPHA DRMs, described in the paragraphs that follow.

So, with that background, it's time now to dive into the details of the Design Reference Missions.

The SPS-ALPHA Design Reference Missions

The Design Reference Missions (DRMs) for SPS-ALPHA defined thus far are:

- DRM-0, an early small-scale ground-based testbed that may also be deployed as a technology flight experiment precursor to DRM-1;
- DRM-1, an initial low-power low Earth orbit (LEO) technology flight demonstration (TFD);
- DRM-2, an integrated, moderate power LEO technology flight demonstration;
- DRM-3, a geostationary Earth orbit (GEO) based SPS pilot plant (at sub-scale);
- DRM-4, an initial full-scale GEO-based SPS (first system); and,

- DRM-5, representing large-scale GEO-based recurring SPS platforms (i.e., for the second and later full-scale Solar Power Satellites).

The paragraphs that follow discuss the details of each DRM, including the quantitative results of the NIAC study systems analysis as well as the number and masses of various modules and the cost estimate for each.[3]

DRM-0: Early Technology Testbed

Before attempting DRM-1, technology developments and demonstrations are needed to sort out the details of the module designs that will comprise SPS-ALPHA and the interfaces among them. It seems likely that "trying out" different options in a testbed will be extremely useful. This testbed is "DRM-0," which is the only one that was not defined during the NIAC study. If the ground-based version of the testbed development goes well, then a short duration technology flight experiment in low Earth orbit might well be considered. Table 10-3 summarizes the notional specifications for this testbed.

As a technology effort, the cost estimation task for DRM-0 is somewhat different from that for a flight project. However, in the absence of detailed estimates, a rough rule of thumb is that R&D should require about 10% of the investment that the first flight unit will entail. On that basis, the total cost for the ground testbed should be approximately $10M (not including the cost for a possible LEO flight technology experiment).

Table 10-3 Summary of Preliminary Mass Statement of DRM-0

Mass Statement by Module				Mass Statement by Assembly	
Module	Number of Modules	Ave. Unit Mass (kg)	Total Mass (kg)	Assembly	Assy Mass (kg)
HexBus Modules	18	13.9	250	Primary Array Assembly (PAA)	259
Interconnects	120	1.0	120	Solar Reflector	239
HexFrame Structures	30	13.6	408	Primary Structure	204
Reflector Deployment Module (RDM)	12	4.0	48	Connecting Truss	227
Solar Power Generation (SPG) Module	7	5.1	35.7	Propulsion & Attitude Control	77.7
Wireless Power Transmission (WPT) Module	7	12.0	84	Modular HexaBot Assembly (MHA)	79
Propulsion & Attitude Control (PAC) Module	1	10.0	10		
Modular Autonomous Robotic Equipment" (MARE)	12	10.0	120		
Initial Propellant Load	1	10.0	10		
				Total Platform Hardware Mass (kg)	1,085.7 kg

DRM-1: Initial Small-Scale Technology Demonstration in LEO

"Design Reference Mission One" (DRM-1) would be a relatively small-scale technology flight demonstration (TFD) of the key systems and initial technologies of the SPS-ALPHA platform in low Earth orbit (LEO). DRM-1 would validate both "off-the-shelf" and "off-the-workbench" technologies in an initial version of the SPS-ALPHA architecture, including testing of all major platform systems (e.g., modules and assemblies) and technologies (including electric propulsion and robotics). DRM-1 would probably not be large enough to transmit an effective amount of power to Earth-based receivers. However, all of the technologies for space-to-ground or space-to-space power transmission would be tested.

During the Phase I NIAC study of SPS-ALPHA, a baseline case for DRM-1 was defined. The platform was modeled as involving an ellipsoid version of the Primary Structure Assembly (PSA) as described in Chapter 5. Table 10-4 presents the mass statement for DRM-1.[4] Table 10-5 presents the results of a preliminary cost estimate for SRM-1, including the costs of hardware and propellants.

Table 10-3 Summary of Preliminary Mass Statement of SPS-ALPHA DRM-1

Mass Statement by Module				**Mass Statement by Assembly**	
Module	Number of Modules	Ave. Unit Mass (kg)	Total Mass (kg)	Assembly	Assy Mass (kg)
HexBus Modules	280	13.9	3,886	Primary Array Assembly (PAA)	7,812
Interconnects	1,674	1.0	1,674	Solar Reflector	1,566
HexFrame Structures	159	13.6	2,165	Primary Structure	1,997
Reflector Deployment Module (RDM)	29	4.0	116	Connecting Truss	300
Solar Power Generation (SPG) Module	223	5.1	1,133	Propulsion & Attitude Control	354
Wireless Power Transmission (WPT) Module	217	12.0	2,604	Modular HexaBot Assembly (MHA)	79
Propulsion & Attitude Control (PAC) Module	6	10.0	60		
Modular Autonomous Robotic Equipment" (MARE)	41	10.0	410		
Initial Propellant Load	6	10.0	60		
			Total Platform Hardware Mass (kg)		12,108 kg

Table 10-4 DRM-1 Hardware Cost Estimation Results (30 kW @ Earth)

Sensitivity Outputs	Initial CER ($/kg)	Unit Mass (kg)	Number of Modules	Total Mass (MT)	Final CER ($/kg)
HexBus Modules	$250,000	14	280	3.9	$4K-$6K
Interconnects	$250,000	1	1,674	1.7	$2K-$3K
HexFrame Structures	$50,000	14	159	2.2	$1K-$2K
Reflector Deployment Module (RDM)	$100,000	4	29	0.1	~$9K
Solar Power Generation (SPG) Module	$250,000	5	223	1.1	~$6K
Wireless Power Transmission (WPT) Module	$250,000	12	217	2.6	~$6K
Propulsion & Attitude Control (PAC) Module	$250,000	10	6	0.1	$50K-$80K
Modular Autonomous Robotic Equipment" (MARE)	$250,000	10	41	0.4	$15K-$22K
0.5-Year Propellant Load	$10,000	10	6	0.1	~$2K
Totals	N/A	N/A	~ 2,500	12.1	N/A

There are, of course, a wide variety of alternative cases for DRM-1 that might be defined – for example, involving different types of solar power generation (SPG) technology, different materials for key structures, and so on. The baseline case involved a capacity to deliver – hypothetically – power of total 30 kW to the ground. (Recall that at this small scale, the intensity of the WPT transmission at Earth would be far too low to allow any meaningful power to be collected.) Also, the size of the DRM-1 platform was chosen to enable it to be launched on a single expendable launch vehicle (ELV), but still large enough to be useful in demonstrating launch on more than one vehicle as an aspect of proving the key technologies for space assembly.

Prior to implementing DRM-1, it may be useful to conduct smaller-scale precursor technology flight experiments (TFEs) in LEO. For example, a very small-scale orbiter (e.g., DRM-0) could be staged on a small ELV, piggybacked with another payload on a larger ELV, or staged from the International Space Station (ISS). Such precursor missions could be used to demonstrate the key functions of the PAA (Primary Array Assembly), such as the wireless power transmission from space to ground and solar power generation (SPG) module, as well as higher-risk platform capabilities, such as deployment of multiple HexFrame Structural Modules.

With a mass of just more than 12 MT, the total estimated hardware cost of the hyper-modular DRM-1 is \$56M-\$73M. This mission would focus on validating the core platform systems for SPS-ALPHA and set the stage for a fully integrated follow-on demonstration at larger-scale.

DRM-2: Moderate-Scale Integrated Technology Demonstration in LEO

“Design Reference Mission Two” (DRM-2) would be a moderate-scale demonstration in low Earth orbit, envisioned as a “dress rehearsal” for the automated and tele-supervised deployment of large-scale solar power satellites in GEO. DRM-2 is defined to deliver 200 kW to receivers on Earth from LEO. It is not expected that DRM-2 will deliver commercially viable amounts of power; nevertheless, the platform may have significant space applications (see Chapter 11). Table 10-6 presents the detailed mass statement for the DRM-2[5] and Table 10-7 presents the results of a preliminary cost estimate. As was the case for DRM-1, the size of this system is still too small to allow meaningful power to be transmitted.

Table 10-5 Summary of Preliminary Mass Statement of SPS-ALPHA DRM-2

Mass Statement by Module				**Mass Statement by Assembly**	
Module	Number of Modules	Ave. Unit Mass (kg)	Total Mass (kg)	Assembly	Assy Mass (kg)
HexBus Modules	445	13.9	6,177	Primary Array	7,812
Interconnects	2,658	1.0	2,658	Solar Reflector	1,566
HexFrame Structures	214	7.0	1,498	Primary Structure	1,997
Reflector Deployment Module (RDM)	35	2.0	70	Connecting Truss	300
Solar Power Generation (SPG) Module	337	5.1	1,703	Propulsion & Attitude Control	354
Wireless Power Transmission (WPT) Module	331	12.0	3,972	Modular HexaBot	79
Propulsion & Attitude Control (PAC) Module	6	10.0	60		
Modular Autonomous Robotic Equipment” (MARE)	57	10.0	570		
Initial Propellant Load	6	10.0	60		
				Total Platform Hardware Mass (kg)	16,768

Table 10-6 DRM-2 Hardware Cost Estimation Results (200 kW @ Earth)

Sensitivity Outputs	Initial CER ($/kg)	Unit Mass (kg)	Number of Modules	Total Mass (MT)	Final CER ($/kg)[6]
HexBus Modules	$250,000	14	445	6.2	$4K-$6K
Interconnects	$250,000	1	2,658	2.7	$1K-$2K
HexFrame Structures	$50,000	7	214	1.5	$1K-$2K
Reflector Deployment Module (RDM)	$100,000	2	35	0.1	~$9K
Solar Power Generation (SPG) Module	$250,000	5	337	1.7	$4K-$6K
Wireless Power Transmission (WPT) Module	$250,000	12	331	4.0	$4K-$6K
Propulsion & Attitude Control (PAC) Module	$250,000	10	6	0.1	$30K-$50K
Modular Autonomous Robotic Equipment" (MARE)	$250,000	10	57	0.6	$9K-$14K
0.5-Year Propellant Load	$10,000	10	6	0.1	$1K-$2K
Totals	N/A	N/A	~ 4,000	16.8	N/A

The baseline DRM-2 case was modeled as an ellipsoid version of the Primary Structure Assembly (PSA) as described in Chapter 5. It involves a set of technology selections and includes those that are currently in use for other space applications. DRM-2 would also accommodate several TFEs addressing more advanced technologies (such as those that might be incorporated in the DRM-3 system). With a total mass of almost 17 MT, the estimated hardware cost of the modular DRM-2 is approximately \$61.2M-\$94.3M. This mission would establish both advanced components for the SPS-ALPHA architecture and key systems (e.g., robotics) needed for deployment and operations in GEO. At this point, all the key technologies needed for an initial SPS would be ready.

DRM-3: Initial Technology Demonstration in GEO: a Sub-Scale Pilot Plant

The objective of "Design Reference Mission Three" (DRM-3) would be to deploy and operate the first large – but still sub-scale – integrated demonstration of SPS-ALPHA in geostationary Earth orbit, with the capability to deliver solar power from space to premium and/or isolated markets on Earth. Two alternative cases for DRM-3 were defined during the NIAC study, one to deliver 2 MW and the other to deliver 18 MW, both to terrestrial markets from a GEO operational orbit.

The two DRM-3 cases of the SPS-ALPHA platform were modeled as involving a Sigmoid-type version of the Primary Structure Assembly (PSA) as described in Chapter 5. The two cases involved the same set of specific technology selections and differed only in terms of scale. Table 10-8 below presents the detailed mass statement for the DRM-3 (at 2 MW) system; a summary of the DRM-3 (at 18 MW) system mass statement is presented in Table 10-9 following. The two cases for DRM-3 bracket the mass of the ISS (at some 450 MT), but would be based in GEO rather than LEO, and in either case would be dramatically lower in cost. Also, because at 2.45 GHz the WPT antenna in GEO for both cases is relatively small compared to the standard 1,000 m diameter (discussed in Chapter 4), the area on Earth over which the RF beam will be spread must be quite large. Determination of the actual power received will require additional, more detailed analysis.[7]

Table 10-8 Preliminary Mass Estimates for SPS-ALPHA DRM-3 (@ 2 MW)

Mass Statement by Module				Mass Statement by Assembly	
Module	Number of Modules	Ave. Unit Mass (kg)	Total Mass (kg)	Assembly	Assy Mass (kg)
HexBus Modules	2,365	24	57,062	Primary Array	222,362
Interconnects	14,178	1	14,178	Solar Reflector	1,001
HexFrame Structures	214	7	1,498	Primary Structure	2,047
Reflector Deployment Module (RDM)	35	2	70	Connecting Truss	168
Solar Power Generation (SPG) Module	2,319	21	48,699	Propulsion & Attitude Control	6,850
Wireless Power Transmission (WPT) Module	2,269	47	106,643	Modular HexaBot	182
Propulsion & Attitude Control (PAC) Module	50	16	800		
Modular Autonomous Robotic Equipment" (MARE)	76	10	760		
Initial Propellant Load	50	58	2,900		
			Total Platform Hardware Mass (kg)		232,610

Table 10-9 Preliminary Mass Estimates of SPS-ALPHA DRM-3 (@ 18 MW)

Mass Statement by Module				Mass Statement by Assembly	
Module	Number of Modules	Ave. Unit Mass (kg)	Total Mass (kg)	Assembly	Assy Mass (kg)
HexBus Modules	10,301	24	248,738	Primary Array	972,062
Interconnects	61,782	1	61,782	Solar Reflector	20,679
HexFrame Structures	552	55	30,130	Primary Structure	26,559
Reflector Deployment Module (RDM)	113	80	9,040	Connecting Truss	2,688
Solar Power Generation (SPG) Module	10,019	21	210,399	Propulsion & Attitude Control	22,900
Wireless Power Transmission (WPT) Module	9,919	47	466,193	Modular HexaBot	364
Propulsion & Attitude Control (PAC) Module	100	36	3,600		
Modular Autonomous Robotic Equipment (MARE)	237	10	2,370		
Initial Propellant Load	100	130	13,000		
			Total Platform Hardware Mass (kg)		1,045,252

Although the focus here is on the platform, it is also important to recall that DRM-3 would also demonstrate essential in-space transportation systems. A SEP OTV is assumed as the lowest cost solution as we discussed in Chapter 7, and the CER used is that presented in Table 10-2. The detailed cost estimation relationships for the larger DRM-3 (delivering 18 MW to Earth) is shown in Table 10-10; as suggested, the cost is significantly lower than the hardware cost realized for the ISS. The projected cost of platform fabrication is a remarkable $678 M, for a total platform mass of roughly 1,045 MT – considerably less than the cost of the ISS as hoped. If this can be achieved, it will be due to the hyper-modular architecture used in the platform.

Table 10-10 DRM-3 Hardware Cost Estimation Results (18 MW @ Earth)

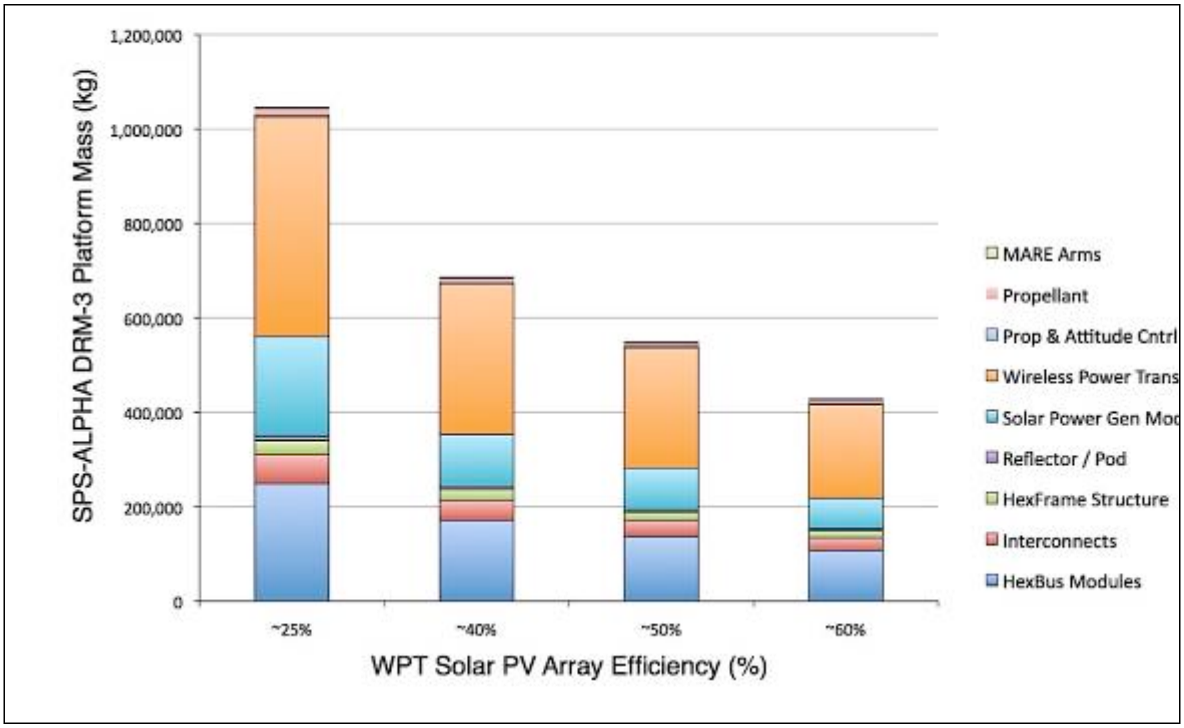
Sensitivity Outputs	Initial CER ($/kg)	Unit Mass (kg)	Number of Modules	Total Mass (MT)	Final CER ($/kg)[8]
HexBus Modules	$250,000	24	10,301	248.7	~$500-$700
Interconnects	$250,000	1	61,782	61.8	$200[9]
HexFrame Structures	$50,000	55	552	30.1	~$800
Reflector Deployment Module (RDM)	$100,000	80	113	9.0	~$4K
Solar Power Generation (SPG) Module	$250,000	21	10,019	210.4	~$500-$700
Wireless Power Transmission (WPT) Module	$250,000	47	9,919	466.2	~$500-$700
Propulsion & Attitude Control (PAC) Module	$250,000	36	100	3.6	~$9K
Modular Autonomous Robotic Equipment" (MARE)	$250,000	10	237	2.4	~$6K
0.5-Year Propellant Load	$10,000	130	100	13.0	$400
Totals	N/A	N/A	~ 110,000	1,045.3	N/A

Based on the CERs, the cost of space transportation (ETO and in-space) is estimated at about \$3.1B, and the total installed cost in space would therefore be some \$3.8B. Assuming that the receiver is sized to collect only 10MW (rather than the full 18 MW), the installed cost per watt is about \$170 per watt, and the cost of energy over a 10-year lifetime is in the vicinity of \$2 per kW-hour.[10]

DRM-3 / Sensitivity Study 1: Variation of SPG Efficiency and Specific Mass

The first sensitivity study that we will discuss involves varying solar power generation efficiency and specific mass. For this analysis, the larger DRM-3 version of SPS-ALPHA (at 18 MW) was used as the baseline, with an assumed solar array efficiency of 25% (well within the state of the art).[11] As before, the concentration ratio was held at fixed, as was the total power delivered to Earth. As can be seen in Figure 10-2, varying the WPT technology has a significant impact on overall platform mass. This is due to the change in Primary Array Assembly (PAA) mass per unit area, as well as changes in the required reflector systems to provide sunlight to the SPG (Solar Power Generation) module.

Figure 10-2 Impact of Variations in SPG Efficiency (DRM 3 @ 18 MW)



DRM-4: First Solar Power Satellite in GEO

"Design Reference Mission Four" (DRM-4) is defined to be the first "full-scale" SPS in GEO, scaled to deliver approximately 500 MW to terrestrial markets from a GEO operational orbit with the expectation that the cost per kilowatt-hour would still be somewhat higher than the target for commercial baseload power. See Table 10-11 for a summary of the detailed mass statement of this case. During the NIAC Phase 1 study, the DRM-4 SPS-ALPHA platform was modeled with a Sigmoid-type version of the PSA, as described in Chapter 5, and involved the set of specific technology selections discussed in Chapter 14.

The module-by-module details of the cost estimate for the DRM-4 platform are presented in Table 10-12. The overall fabricated hardware cost of the initial platform is estimated at approximately \$2.9B and, with the space transportation cost for a platform mass of 11,795 MT plus the fabrication cost of the ground receiver, the total installed cost is approximately \$16B. This is a large number, but far, far less than the \$300B-\$1,000B in current year dollars estimated for the first platform of the 1979 SPS Reference System type.

The installed cost of power is at a level of \$32 per watt – far too high, but a dramatic reduction from the cost of power for DRM-3 case we looked at previously. When examined over a 30-year lifetime (and including operations and maintenance as well as replacing failed components as we discussed above), the cost of energy becomes roughly 24¢ per kWh, which is actually comparable to the early LCOE for a number of different sustainable energy options that have come into service during the past 25 years.

As shown, DRM-4 involves a dramatic increase beyond the scale of DRM-3; more than a 10-fold increase in the number of modules, and 20-fold or more increase in the power delivered to the ground-based receiver. This platform finally reaches a scale at which the size of the transmitter is large enough to accomplish relatively efficient end-to-end power transmission at microwave WPT wavelengths.

The deployment of DRM-4 would also be the first time that a new reusable launch vehicle (RLV) and the transportation of required in-space transportation equipment and propellants would be fully integrated into the SPS CONOPS. With the accomplishment of DRM-4, all of the pieces of the puzzle are in place: large-scale SPS may be deployed to deliver Space Solar Power to Earth.

Table 10-11 Preliminary Mass Statement of SPS-ALPHA DRM-4

Mass Statement by Module				**Mass Statement by Assembly**	
Module	Number of Modules	Ave. Unit Mass (kg)	Total Mass (kg)	Assembly	Assy Mass (kg)
HexBus Modules	131,808	24	3,172,795	Primary Array	10,873,795
Interconnects	790,722	1	790,722	Solar Reflector	313,250
HexFrame Structures	8,360	54	452,540	Primary Structure	351,350
Reflector Deployment Module (RDM)	1,750	79	138,250	Connecting Truss	62,400
Solar Power Generation (SPG) Module	128,127	8	1,025,016	Propulsion & Attitude Control	192,600
Wireless Power Transmission (WPT) Module	127,927	47	6,012,569	Modular HexaBot	1,876
Propulsion & Attitude Control (PAC) Module	200	195	39,000		
Modular Autonomous Robotic Equipment (MARE)	2,078	10	143,600		
Initial Propellant Load	200	718	20,779		
			Total Platform Hardware Mass (kg)		11,795,271

Table 10-12 DRM-4 Hardware Cost Estimation Results (500 MW @ Earth)

Sensitivity Outputs	Initial CER ($/kg)	Unit Mass (kg)	Number of Modules	Total Mass (MT)	Final CER ($/kg)[12]
HexBus Modules	$250,000	24	131,808	3,172.8	~$200
Interconnects	$250,000	1	790,722	790.7	~$200
HexFrame Structures	$50,000	54	8,360	452.5	~$300
Reflector Deployment Module (RDM)	$100,000	79	1,750	138.3	$2K
Solar Power Generation (SPG) Module	$250,000	8	128,127	1,025.0	~$200
Wireless Power Transmission (WPT) Module	$250,000	47	127,927	6,012.6	~$200
Propulsion & Attitude Control (PAC) Module	$250,000	195	200	39.0	~$6K
Modular Autonomous Robotic Equipment (MARE)	$250,000	10	2,078	20.8	~$1K-$2K
0.5-Year Propellant Load	$10,000	718	200	143.6	~$250
Totals	N/A	N/A	~ 1,200,000	11,795.3	N/A

DRM-5: Recurring Integrated GEO SPS-ALPHA for Commercial Markets

Following the first full-scale SPS and incorporating a range of technology innovations validated as TFEs during DRM-4, recurring SPS-ALPHA platforms – designated as "Design Reference Mission Five" (DRM-5) – would be deployed. These would involve larger platforms and the delivery of greater power levels than those involved in DRM-4. DRM-5 was defined to deliver 2,000 MW (2 GW) to terrestrial markets from a GEO operational orbit, targeting commercial baseload markets at a competitive price. An important role for each new full-scale SPS-ALPHA will be to accommodate a range of TFEs that test advanced technology options for later deployment. Table 10-13 presents the detailed characteristics of the baseline DRM-5 case. The SPS-ALPHA platform in the DRM-5 case was modeled with a Sigmoid-type version of the PSA as described in Chapter 5, and involved the set of specific technology selections summarized in Chapter 15.

Table 10-14 presents the detailed cost estimates by module type for the baseline DRM-5; the total initial hardware cost works out to be appropriately \$5.7B. With a platform mass of 34,814 MT and a receiver cost of roughly \$700M, the total installed cost for DRM-5 (the baseline case) is therefore \$41.2B, or some \$20.5 per watt over a 30-year period. The levelized cost of electricity for this case is then about 15.7¢ per kWh. This value, as we will see in Chapter 12 (concerning the terrestrial energy market), is still a bit too high for commercial baseload power. However, the technology assumptions used for the baseline DRM-5 were deliberatively conservative. (For example, it was assumed that the primary structural elements would be fabricated from aluminum rather than a lighter weight structure, such as a carbon composite material.) With selected improvements in specific platform technologies, a significant reduction in cost may be achieved.

To explore the impact of those technology enhancements, several sensitivity studies were performed with the starting point being the baseline DRM-5 as shown in Table 10-13. The technology improvements incorporated included: (1) the modest reductions in specific mass (i.e., improving on the baseline use of aluminum for HexBus structural materials); (2) improvements in the mass per unit area of the WPT system; and (3) increases in the allowable concentration ratio for reflectors and Primary Array. The results of these sensitivity studies are discussed below.

Table 10-13 Mass Statement of SPS-ALPHA DRM-5 (2 GW @ Earth)

Mass Statement by Module				**Mass Statement by Assembly**	
Module	Number of Modules	Ave. Unit Mass (kg)	Total Mass (kg)	Assembly	Assy Mass (kg)
HexBus Modules	392,341	24	9,438,210	Primary Array	32,590,615
Interconnects	2,353,662	1	2,353,662	Solar Reflector	770,595
HexFrame Structures	18,444	54	1,002,186	Primary Structure	833,649
Reflector Deployment Module (RDM)	4,305	79	340,095	Connecting Truss	62,400
Solar Power Generation (SPG) Module	383,619	8	3,068,952	Propulsion & Attitude Control	551,000
Wireless Power Transmission (WPT) Module	383,419	47	18,020,693	Modular HexaBot	5,623
Propulsion & Attitude Control (PAC) Module	200	578	115,600		
Modular Autonomous Robotic Equipment (MARE)	4,888	10	48,884		
Initial Propellant Load	200	2,128	425,600		
			Total Platform Hardware Mass (kg)		34,813,882

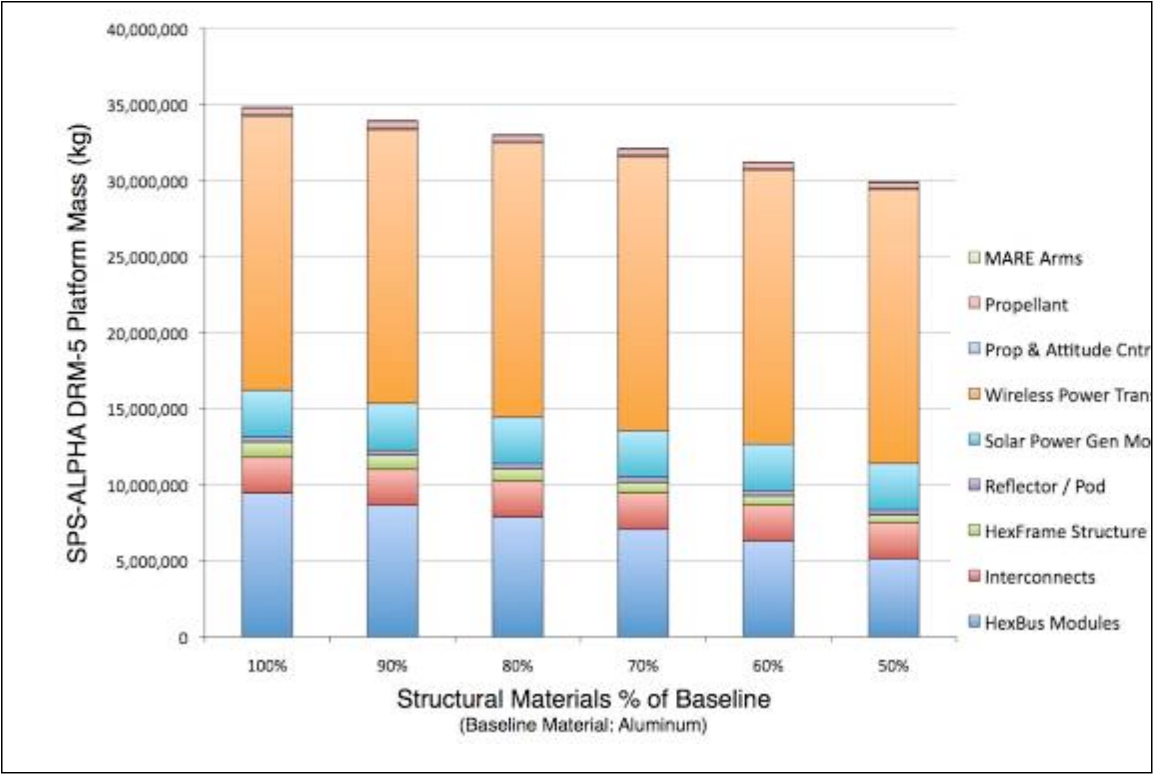
Table 10-14 DRM-5 Hardware Cost Estimation Results (2 GW @ Earth)

Sensitivity Outputs	Initial CER ($/kg)	Unit Mass (kg)	Number of Modules	Total Mass (MT)	Final CER ($/kg)[13]
HexBus Modules	$250,000	20	337,330	6,770.6	~$200
Interconnects	$250,000	1	2,023,650	2,023.7	~$200
HexFrame Structures	$50,000	43	19,878	856.9	~$200
Reflector Deployment Module (RDM)	$100,000	79	4,662	368.3	$400
Solar Power Generation (SPG) Module	$250,000	8	327,891	2,623.1	~$200
Wireless Power Transmission (WPT) Module	$250,000	37	327,691	12,124.6	~$200
Propulsion & Attitude Control (PAC) Module	$250,000	472	200	94.4	~$6K
Modular Autonomous Robotic Equipment (MARE)	$250,000	10	5,190	51.9	~$700-$1K
0.5-Year Propellant Load	$10,000	1,737	200	347.4	~$250
Totals	N/A	N/A	~ 3,000,000	25,260.8	N/A

DRM-5 / Sensitivity Study 1: Variation of Structural Materials Density & Mass

The first sensitivity study examined the variations in overall DRM-5 platform mass for variations in the density of selected structural materials, assuming fixed structural performance (e.g., bending moments, vibration propagation, etc.). The materials chosen for variation were those involved in the structure of the HexBus Modules (kg/m3) and the HexFrame Structural Modules (kg/m). Figure 10-3 presents the results of a series of five cases that were examined in which the FOMs were varied from a baseline (in the case of the HexBus structure this was aluminum) by a given percentage difference.

Figure 10-3 Impact of Variations in the Mass of Structural Materials (D5/S1)

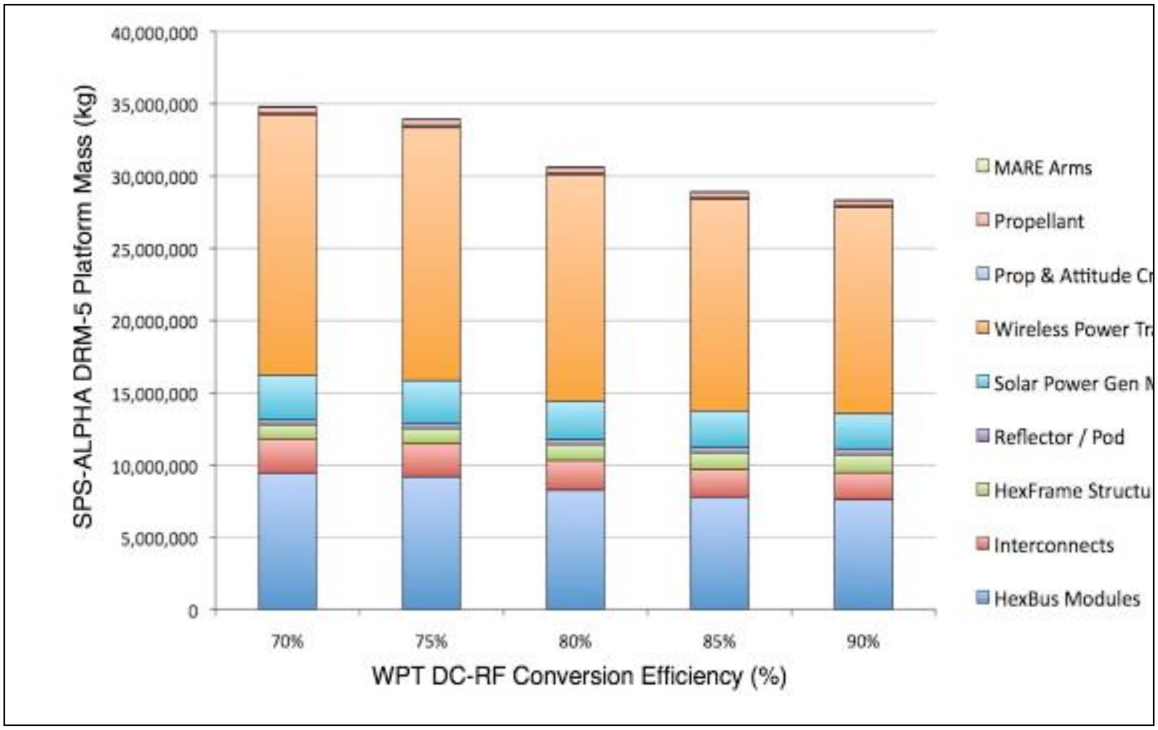


Generally speaking, because the structural systems examined are a relatively small fraction of the total mass and cost of the SPS-ALPHA platform, even relatively deep reductions (e.g., by 50%) in the assumed density of those materials results in a relatively modest (15%) reduction in the overall mass of the platform. However, even this modest percentage reduction represents a savings of some 5,000 MT in platform mass and roughly 10,000 MT in launched mass (when in space propellant requirements are taken into account). This is a huge savings and, as a result, advances in structures and materials become a priority for future R&D.

DRM-5 / Sensitivity Study 2: Variation of WPT DC-RF Conversion Efficiency

This sensitivity study examined the consequences of varying the efficiency with which the WPT system converted DC power input into RF power output. This variation was performed while holding fixed the power delivered to Earth and the concentration ratio for the platform (reflectors to PAA). The result was a decrease in the power required for the same amount of RF power output – which in turn led to reduced mass for the platform. See Figure 10-4 for the results of this analysis.

Figure 10-4 Impact of Variations in the DC-RF Conversion Efficiency (D5/S2)

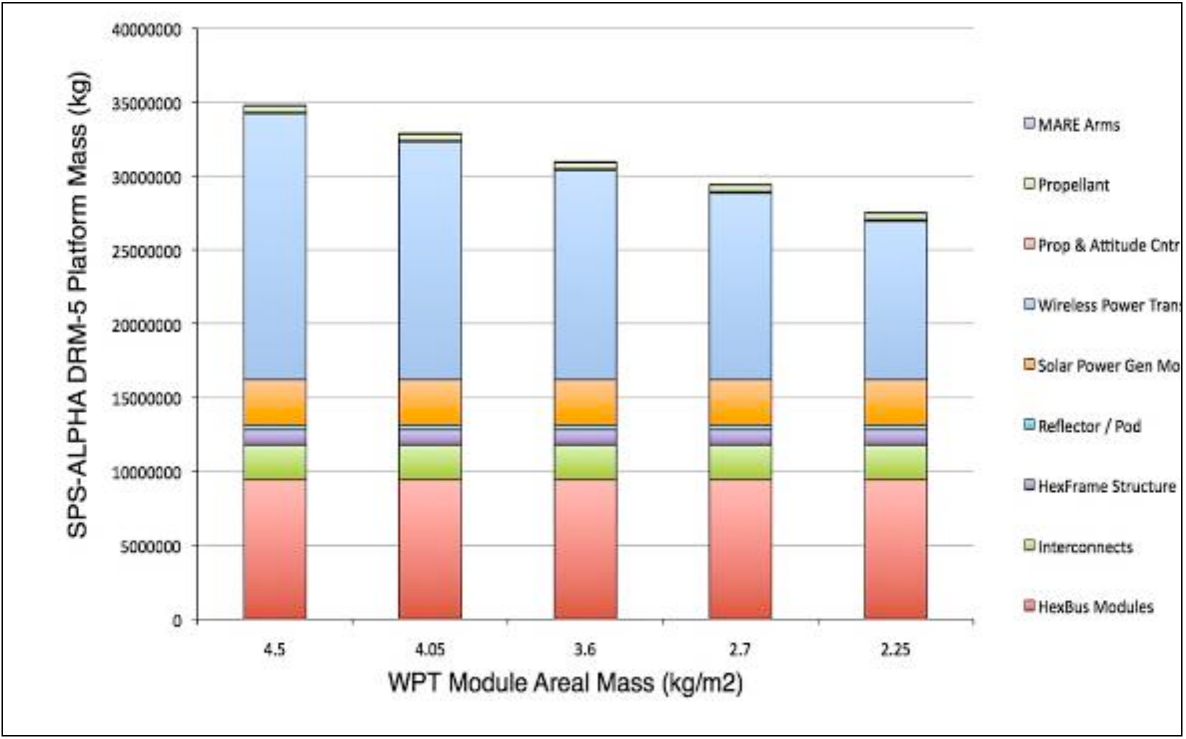


Note that for all of the DRM case studies the estimates of the number of MHA assemblies were quite preliminary. Future studies must address this topic in greater detail and will require more in-depth formulation of a concept of operations (CONOPS) and implementation of operational simulations to refine those estimates. However, as shown in Figure 10-6, even if the estimated number of MHA units were increased significantly, this Assembly would remain a small fraction of the total mass. (And, owing to the strategy of building assembly and maintenance robots from modules – such as the Hexbus – that are used elsewhere in the SPS-ALPHA platform, the MHAs should remain a small contributor to overall cost.)

DRM-5 / Sensitivity Study 3: Variation of WPT Areal Mass

This sensitivity study examined the effect of variations in the mass per unit area of the WPT modules within the Primary Array, holding all other parameters constant. As before, the concentration ratio was fixed, as was the total power delivered to the receiver on Earth. The results are presented in Figure 10-5.

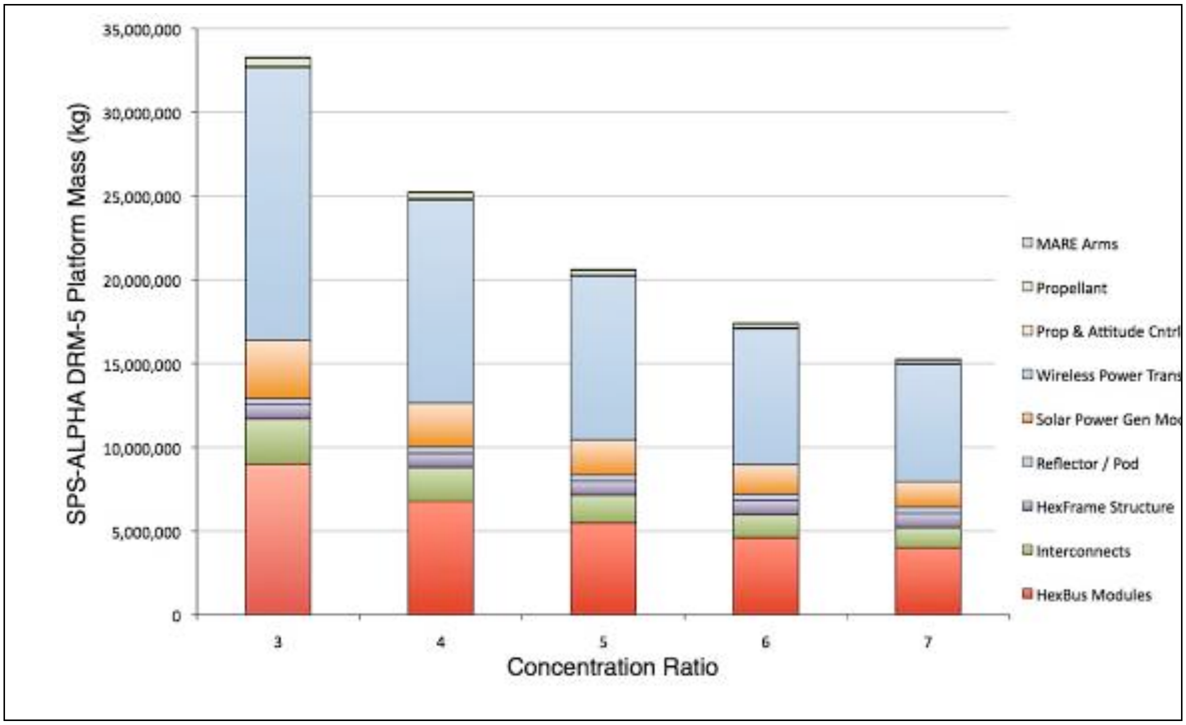
Figure 10-5 Impact of Variations in the Areal Mass of the WPT Modules (D5/S3)



DRM-5 / Sensitivity Study 4: Variation of Concentration Ratio[14]

DRM-5 Sensitivity Study 4 (D5/S4) examines the potential benefit (at the architecture level) of introducing novel materials and devices that operate with performance degradation at significant higher temperatures than can devices (and the materials from which they are fabricated) available at this time. This question was examined by means of architecture level changes that would result from allowing the concentration ratio to increase (which would increase the temperature at the PAA). These results are highly preliminary, but very suggestive for the prioritization of future technology R&D. See Figure 10-6 for a summary of these initial results. For example, they show that increasing the concentration ratio from 3-to-1 to 5-to-1 would reduce the SPS-ALPHA platform mass by almost 15,000 tons – a remarkable result.

Figure 10-6 Impact of Variations in the Concentration Ratio (D5/S4)



Concluding Observations

This Chapter described the details of six SPS-ALPHA DRMs that form the building blocks from which the case for Space Solar Power is constructed. Each step toward the full-scale platform (DRM-5) represents a major validation of technology, systems, and operations at increasing scale, as well as a necessary increase in the scale of manufacturing for the various modules that comprise the platform. Figure 10-7 summarizes the relationship between two high-level characteristics of the several DRMs: the normalized number of modules and the average cost per unity mass ($/kg). As shown in the figure, the number of modules follows (approximately) the well-known *Logistic Function*.[15] This is a strategic result; the purpose of this increase in modules from one to the next was to optimize the scale-up in production from DRM-1 (the first demonstration) to DRM-5 (the last).

Figure 10-7 Increasing Numbers of Modules, Decreasing Cost per Kg

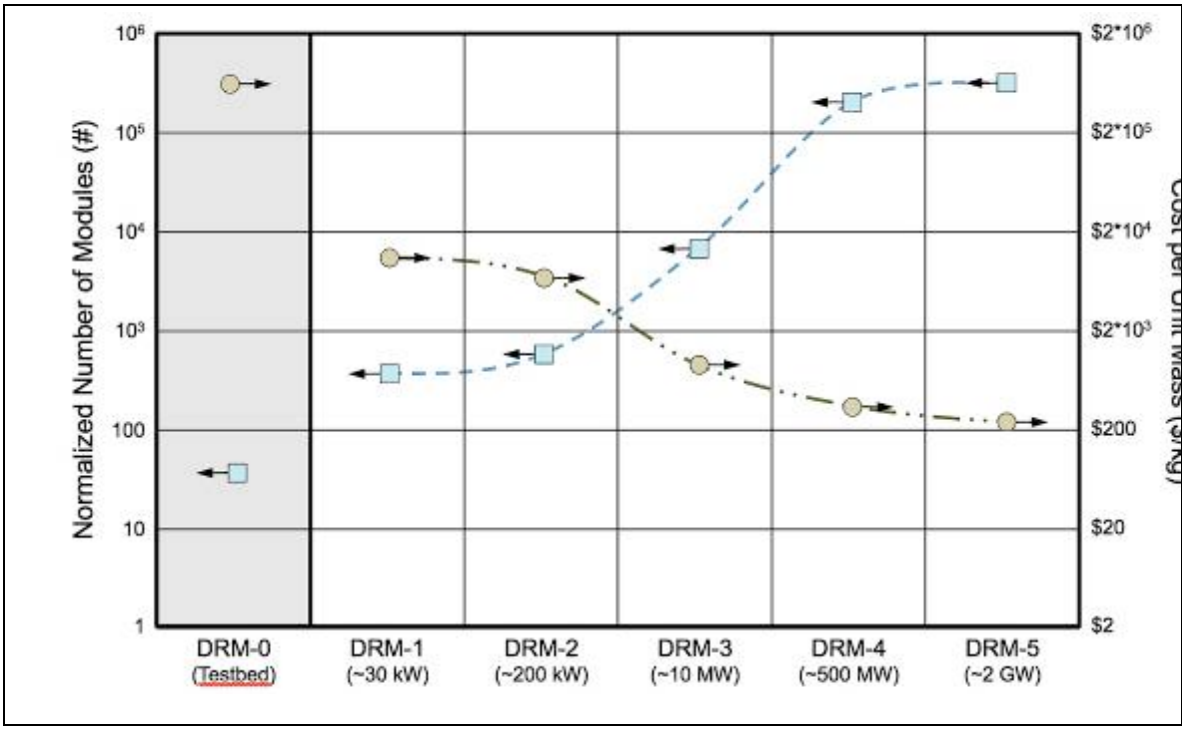


Image Credit: Artemis Innovation Management Solutions LLC

The Chapter also sketched several sensitivity studies that examined what it would mean if the baseline technology choices for SPS-ALPHA were changed in selected ways. These changes were individually modest; however, taking two or more together – for example, an increase in PV efficiency and a decrease in the WPT mass per unit area – would result in significant reductions in SPS platform mass and cost. Although not necessary to begin development of SPS-ALPHA, these enhancements in baseline technologies will be needed to realize commercially viable SPS.

Given these piece parts and the discussions in the preceding Chapters, we may at last turn our attention to the purposes for pursuing Space Solar Power: first identifying potential space applications and then turning our attention to the main point, energy markets on Earth. From these pieces – the DRMs and the market opportunities – Chapter 13 will synthesize an integrated business case for SPS-ALPHA.

[10-1] A higher concentration ratio translates into higher power output per unit mass – a huge advantage, but one that would only become possible with novel devices fabricated from materials that might be able to operate at the higher operating temperatures that would result from higher concentration.

[10-2] As a reminder: the LC/MC works as a percentage adjustment to the cost per unit mass with each doubling of the number of items manufactured. For an initial cost per kilogram of $100 per kilogram, if the LC/MC is 70%, then if the number of items manufactured is doubled, the cost per kilogram is reduced to $70 per kilogram. If the number of items is doubled again, the cost is reduced further to $49 per kilogram (i.e., $100 * 70% * 70% = $49 per kilogram), and so on.

[10-3] For each DRM, it may be assumed that the new technologies and new modules involved will be demonstrated in a subscale ground technology testbed (similar to the initial DRM-0).

[10-4] See Chapter 5 for the definition of the relationships among the modules and the Assemblies.

[10-5] See Chapter 5 for a discussion of the relationships among the modules and the Assemblies that comprise the SPS-ALPHA architecture.

[10-6] Note that in the integrated macroeconomic scenarios that are examined later, DRM-5 follows DRM-4, which follows DRM-3 and so on. In these scenarios, the total number of units manufactured is used as the basis for the CER (not the number in a single DRM). This is reflected in the tables above.

[10-7] It was the former Director of the National Security Space Office (NSSO), Mr. Joseph Rouge, who first posed the question to me in 2007: can something meaningful be done vis-à-vis Space Solar Power in less than 10 years for less than $10B? This was at the end of the independent study done for the NSSO of what was for that effort called "space-based solar power" (SbSP). The result was the "10-10-10" goal: 10 MW to Earth, in 10 years, for less than $10 billion. As it turned out some years later, a hyper-modular SPS option such as SPS-ALPHA can meet – and probably beat – this ambitious challenge for SSP.

[10-8] Note that in the integrated macroeconomic scenarios that are examined later, DRM-5 follows DRM-4, which follows DRM-3 and so on. In these scenarios, the total number of units manufactured is used as the basis for the CER (not just the number of units in a single DRM). This "total number of units" approach is reflected in the tables above.

[10-9] No CER below $200/kg for hardware was allowed, despite the calculation based on the LC/MC, with the assumption that basic component/materials cost "floors" will apply. This CER is approximately consistent with other high technology consumer products (e.g., PCs, tablet computers), mass-produced, but computing intensive machinery (e.g., automobiles), etc.

[10-10] Because the SPS transmitter is comparatively small, the "spot" on the ground is very large, and it is not cost effective to attempt to capture the entire amount of delivered power.

[10-11] Solar array efficiencies as high as 40% have been demonstrated in the laboratory; and, efficiencies on the order of 50% have been discussed for some years (using multi-bandgap PV cells).

[10-12] Note that in the integrated macroeconomic scenarios examined later, DRM-5 follows DRM-4, and so on. In these scenarios, the total number of units manufactured is used as the basis for the CER (not just the number in a single DRM). This "total number of units" is reflected in the tables above.

[10-13] In the macroeconomic scenarios examined later, DRM-5 follows DRM-4, and so on. The total number of units manufactured is used as the basis for the CER (not just the number of units in a single DRM). This "total number of units" approach is reflected in the tables above.

[10-14] As discussed in Chapter 5, the SPS-ALPHA uses large, thin-film mirrors to intercept sunlight and reflect it toward the primary array to become power. The "concentration ratio" is the ratio of the surface area of the mirrors in use divided by the surface area of the primary array (PPA) to which the sunlight is being re-directed.

[10-15] See: https://en.wikipedia.org/wiki/Logistic_function

Chapter 11

Space Missions and Markets

“The Americans have need of the telephone, but we do not. We have plenty of messenger boys."1
Sir William Preece (1876)
Chief Engineer of the British Post Office

Introduction

Historically, space missions have been “power paupers” – constrained in both objectives and design by the limited availability of electrical power and the extremely high cost of that power. For example, the largest geostationary Earth orbit commercial communications satellite has only about 20 kW of onboard power – equivalent to about three to five homes in a typical U.S. neighborhood. Not surprisingly, one reason for – and a consequence of – the lack of large power supplies in space is the extremely high cost per kilowatt-hour delivered by these systems. The largest power system operating in space is on the International Space Station (ISS), with roughly 100 kW of power and a levelized cost of electricity (LCOE) of about \$50-\$100 per kilowatt-hour.[2] As a result, affordable and abundant energy has tremendous market potential for space applications.

There are numerous prospective applications of the SPS-ALPHA architecture, systems and technologies, and supporting infrastructure in space. The range of these potential non-SPS space mission applications includes:

Solar electric power and propulsion systems (SEPS) for human exploration, such as

- High energy SEPS-based Orbital Transfer Vehicles (OTVs) for Earth orbit and inner Solar System operations;
- Multi-megawatt (MMW) SEPS for interplanetary human exploration missions such as Human Mars Missions, (HMM); and
- Advanced SEPS for human exploration robotic precursor missions.

Solar power for Lunar and planetary surface operations, such as

- Power delivered from space to surface systems;
- Power delivered from one point on the surface to another (e.g., from sun-lit locations into permanently shadowed regions); and

- o Power generated locally for systems used to achieve surface access and/or operations.

•Solar power for large Earth-orbiting platforms, such as

- o Very large satellite applications in MEO (middle Earth orbit) and GEO, such as communications satellites (“commsats”);
- o High-power platform applications in LEO, such as government or commercial space stations; and
- o Intermediate power platforms in LEO or MEO, such as satellite constellations.

Propulsion and/or power for outer planet / deep space missions, such as

- o SEP systems for missions traveling to the outer planets;
- o Solar power for deep space missions in the inner Solar System, through the main belt asteroids (and perhaps further); and
- o Solar Sails for deep space / outer planet robotic missions.

Propulsion and/or power for space resources development, such as

- o SEP systems for missions traveling to/from small bodies;
- o SEP systems for small body deflection or retrieval; and
- o Solar power for regolith extraction and processing.

In addition, there are selected special applications of the technologies and/or systems involved. For example, in the case of RF phased array WPT systems, there may also be useful applications of the large aperture systems technologies involved.

This Chapter presents a high-level assessment of some of the potential non-SPS applications of SPS-ALPHA systems, technologies, and supporting infrastructure which represent critically important parts of the overall *Case for Space Solar Power*. The concluding paragraphs summarize the space and nearer-term applications of the SPS-ALPHA architectural approach that are not Solar Power Satellites. They also present thoughts regarding potential relevant future studies and technology developments.

Near-Term Opportunities

In the nearer term, there is one important opportunity for applications of SSP technologies and systems: large aperture and low cost small satellites (aka, “smallsats”) in low or middle Earth orbit.

Since the mid-1990s, a variety of innovative mission applications have involved smallsats in LEO. The best known of these are the 60-plus smallsats of the Iridium constellation, which provide global communications services. Surprisingly, the potential exists to employ system elements of the SPS-ALPHA architecture in this market. The fundamental "Hexbus" described in Chapter 5 and the associated modules (power, RF payload, etc.) can be implemented at almost any scale. As a result, at the smallest level (i.e., less than about 100 kg), smallsats could be launched to and operated in LEO with greater power, larger apertures, and at lower cost than any current systems. The basic systems concept is captured in the discussion below regarding GEO satellites (and as illustrated in Figure 11-3). This is a market that could be served as soon as the next 3-4 years, or any time afterward.

Beginning in the Mid-Term: Markets in Space beyond LEO

In most locations across the Inner Solar System, solar energy is almost always available. SPS-ALPHA would establish the capability to deliver electricity (at roughly $1/kW-hour at about 1%-2% of the current cost at ISS in LEO) to civil or commercial space missions in space, on the Moon, Mars, or small bodies. The availability of reliable, inexpensive, and continuous power at levels of 100s kW to 10s MW or higher would forever change the character of space systems, missions, and goals. Also, ancillary SSP technologies – in areas such as space transportation, space communications, in-space construction, robotics, lightweight structures, and others – would be of immense value to a wide range of civil and commercial space missions. The following paragraphs sketch several prospective space applications of SPS-ALPHA and its major system elements.

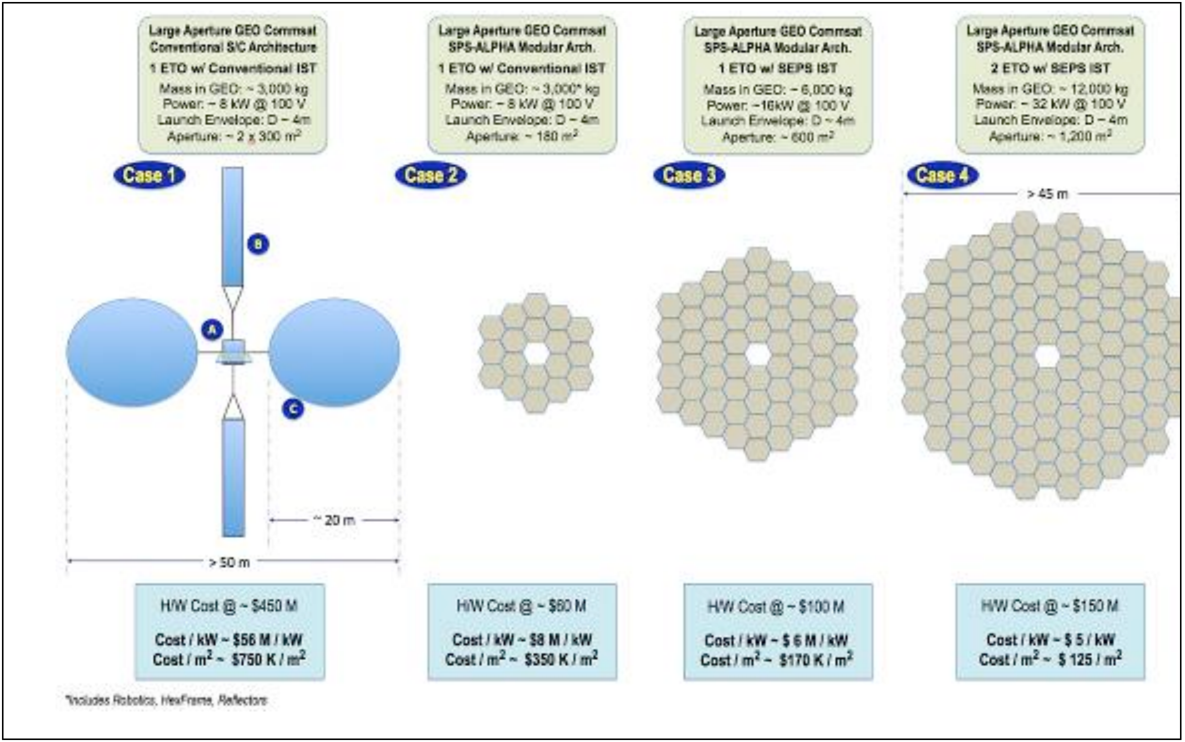
Many current types of Earth-orbiting space mission applications (both commercial and civil government) would benefit from the potential to realize high-power and/or large aperture spacecraft for significantly lower costs. These mission opportunities fall into three broad categories: (1) communications satellites (either in GEO or other orbits); (2) radar satellites (particularly Earth-observing satellites and air traffic control satellites); and (3) optical communications terminal spacecraft (either in Earth orbit or in an orbit such as an Earth-Moon Libration Point). The following are brief descriptions of these potential applications.

Communications Satellites. An enduring goal for communications satellite ("commsat") R&D is to increase the size and power for the spacecraft aperture (the antenna) by which information is sent to and received from users on the ground. Achieving this goal would enable a given commsat to earn more revenues for a given investment by increasing the number of available channels for data transmission and by more tightly focusing each transmission, thereby increasing the platform's ability to reuse its assigned portions of the RF spectrum. However, in the past 20 years, commsats have grown to the point where they have reached existing launch vehicles' carrying capacity limits ~~(~~in terms of weight and physical size~~)~~. Accomplishing further increases in aperture size and power level by means of conventional spacecraft architectures would require significant increases in costs (due to the high costs of large mechanically deployable apertures systems), and would not increase power levels. And, In any case, there are firm limits on the total spacecraft mass that can be realized in GEO given existing launchers and in-space transportation systems.[3]

Advancing the SPS-ALPHA concept would deliver two classes of products / services to the commsat market: (1) applications of technologies and systems in new, modular platforms, and (2) use of supporting infrastructure (e.g., in-space transportation) for both existing or new spacecraft deployment and operations. The latter is straightforward: the deployment of SPS-ALPHA (even in a pilot plant scale) could result in significant reductions in launch and in-space transportation costs for all Earth-orbiting missions. In addition, affordable in-space transportation (AIST) systems, such as SEPS orbital transfer vehicles (OTVs) would greatly increase the payload delivered to GEO, even for conventional spacecraft and existing launchers.

The former opportunities – use of SPS-ALPHA technologies and systems to implement a new type of commsat – are even more promising. Figure 11-1 presents the results of a first-order case study of the GEO commsat market as an example. The hyper-modular SPS-ALPHA architecture with in-space assembly scales up elegantly (consistent with modeling of an early prototype system from the NIAC Phase 1 study) to enable apertures of various sizes that could meet market demands with great flexibility and at costs considerably lower that conventional architecture spacecraft. In addition, the introduction of new in-space transportation systems (such as SEP OTV) will make it possible to stage even larger spacecraft to GEO.

Figure 11-1 Mini-Case Study of a Conventional GEO Commsat as compared to a "Commsat-ALPHA"



Credit: Artemis Innovation Management Solutions LLC (2013)

The figure compares (1) the development and launch of the first of a notional new series of commsats using conventional spacecraft architecture, and (2) development and launch of a series of three alternate modular GEO commsats based on the SPS-ALPHA architecture ("GEO Commsat-ALPHA"). The four cases examined were:

Conventional in-space transportation cases, including

- Case 1: Conventional large commsat; power @ 8 kW, mass @ 3,000 kg; aperture @ 2 x 300m^2
- Case 2: Commsat-ALPHA; power @ 8 kW, mass @ 3,000 kg[4]; aperture @ 180m^2

Advanced in-space transportation cases

- Case 3: Commsat-ALPHA; power @ 16 kW, mass @ 6,000 kg; aperture @ 600m^2
- Case 4: Commsat-ALPHA; power @ 32 kW, mass @ 12,000 kg; aperture @ 1,200m^2

As can be seen in the figure, for equivalent launched mass "Commsat-ALPHA" (with advanced space transportation) case results in an improvement of as much as 9:1 in the cost per kW, and of better than 4:1 in the cost per m^2 of aperture. If SPS-ALPHA can be developed successfully, then an early sub-scale demonstration (e.g., DRM-2, discussed in Chapter 10) would be consistent with a better than 10-fold improvement in communications satellites: 4 times more power and twice the aperture, for less than 1/3 the cost.

Some important notes: in all cases above, launch costs are not included. The level of technology is assumed to be roughly equivalent, but the cost of R&D is not included. Also in all cases, the initial development cost estimation relationship (CER) is assumed to be $150,000/kg.[5] However, in the case of the modular architecture, a learning curve of approximately 70% is applied (see Chapter 6 for additional discussion of this factor and sensitivity of results to the choice of CER). The most significant difference is in the architecture, and a potential for mass production of the system elements in the "Commsat-ALPHA" spacecraft case.

Future studies should examine these potential applications in much greater detail, including more detailed evaluation of the costs for ancillary systems (such as robotics), the potential impact of frequency re-use for the larger aperture cases, and the potential impact on revenues and overall economics for each of the cases examined.

Radar Satellites. In the case of future radar satellites, the analysis should be quite similar to the above case, with the cost per unit of area and the cost per unit of power for a conventional architecture Radarsat versus a "Radarsat-ALPHA" architecture resulting in significant advantage to those cases where a significant improvement in cost due to mass production of spacecraft elements can be realized. Future studies should examine this case in detail, including the impact of frequency requirements for the larger aperture cases, scanning angle requirements and the potential impact on structural flexibility on systems performance.

Optical Communications Terminal Satellites. For decades, a principal objective of NASA investments in the Deep Space Network (DSN) and in on-board communications systems has been to increase the data rates that can be realized with spacecraft in deep space. Increasing the diameter of on-board communications dishes, increasing the size of ground stations, and arraying multiple independent ground stations together to form a large synthetic apertures are all techniques that have been engineered into new space systems over the years.

One visionary option to dramatically improve deep space data rates is to transition from RF to optical (laser) communications links. This concept has been under study and development for the past 30 years or so, and considerable progress has been made in the development of relatively compact optical transceivers with reasonably sized apertures (capable of providing good onboard link performance) that can be placed on board deep space spacecraft in the future. Due to the cost of large space telescopes and space-based laser systems, deep space optical communications concepts usually assume that the Earth-side of the link will be located on Earth's surface (for example, an optical telescope with a laser transceiver located at the DSN station in Goldstone, California).

However, optical telescopes located above the atmosphere might offer significant advantages over telescopes on Earth's surface. For example, with a space-based system, link degradation due to cloud cover or atmospheric attenuation would be eliminated. Signal degradation resulting from stray light interference (e.g., during daytime) could also be reduced. However, the cost of such a terminal, combined with the relatively infrequent need for this capability, represent significant barriers to introducing a space-based optical communications terminal (SbOCT). Figure 11-2 presents a first-order case study of an Earth-Orbiting SbOCT, comparing (1) two cases involving the development and launch of the first of a notional new SbOCT spacecraft using a conventional spacecraft architecture, and (2) one case involving development and launch of an alternate modular Earth-Orbiting SbOCT based on the SPS-ALPHA architecture ("SbOCT-ALPHA"). The cases examined were:

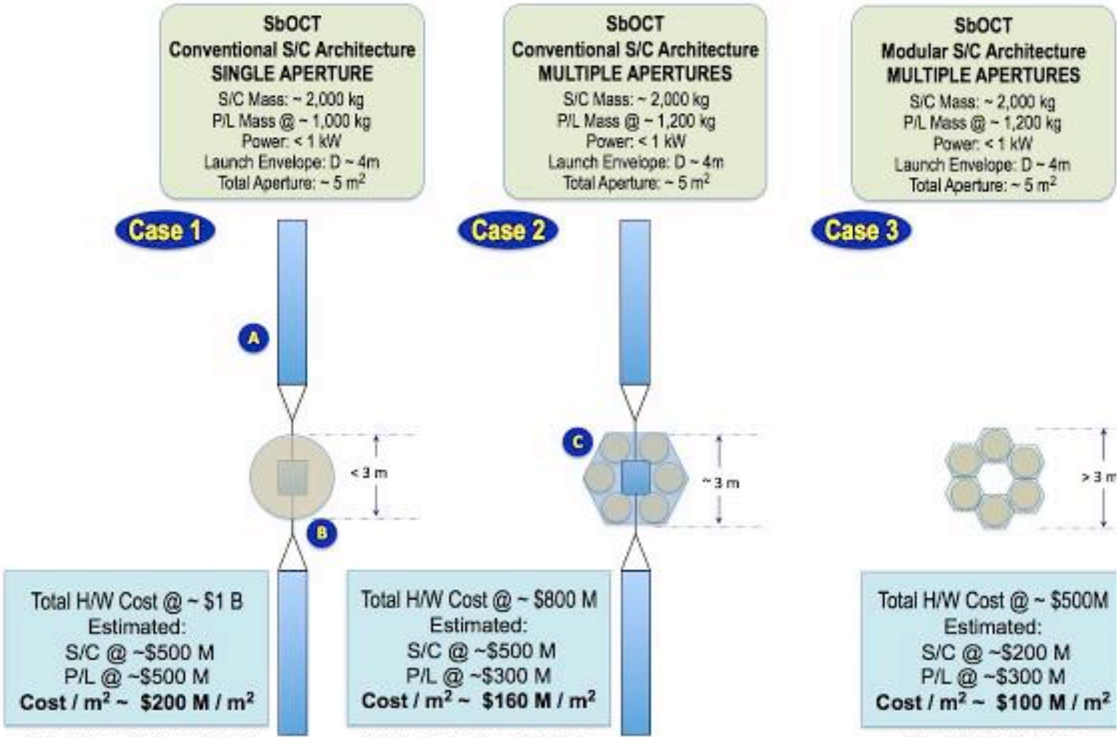
Conventional Spacecraft Architecture Cases

- Case 1: Conventional Satellite, single large aperture 5 m^2; power @ ~ 1 kW, mass @ 3,000 kg; (with 2,000 kg for spacecraft mass, and 1,000 kg for payload mass)
- Case 2: Conventional Satellite, six (6) modular apertures with a total aperture area of 5 m^2; power @ ~ 1 kW, mass @ 3,000 kg; (with 2,000 kg for spacecraft mass, and 1,200 kg for total payload mass)

Modular Spacecraft Architecture Case

- Case 3: Modular Architecture Satellite, six (6) 2-meter diameter HexBuses, plus structure and reflectors, and six (6) modular apertures with a total aperture area of 5 m^2; power @ ~ 1 kW, mass @ 3,000 kg; (with 2,000 kg for spacecraft mass, and 1,200 kg for total payload mass)

Figure 11-2 Conventional Satellite SbOCT vs. a Modular "SbOCT-ALPHA"



Estimate from On-Line References

Derived "Guesstimate" based on Inferred Masses (S/C and P/L)

Derived Estimate based on Case @ "Guesstimate" (S/C & P/L)

In the literature, two alternative cases for a conventional spacecraft architecture Earth-orbit optical communications terminal have been examined: (1) involving a single large telescope, and (2) involving a modular set of telescopes that work in tandem.[6] For purposes of this mini-case study, these two options have been fleshed out (with mass estimates for the spacecraft and payload) and compared to a modular spacecraft architecture based approach. As can be seen in the figure, for equivalent launched mass, the "SbOCT-ALPHA" case may have the potential to improve overall cost by as much as a factor of two (2) compared to the fully monolithic case, and by about 1/3 for the case of a modular optics approach.

Some important notes regarding the SbOCT-ALPHA assessment: in all cases, the launch costs are not included. The level of technology is assumed to be roughly equivalent, but the cost of technology R&D is not included. Also, in all cases the initial development cost estimation relationship (CER) is assumed to be $250,000 per kg for the precision-pointing host spacecraft, and $500,000 per kg for the optical communications payload. For both modular optical architecture (Case 2), and fully modular architecture (Case 3), a learning curve of approximately 70% is applied (see Section 5 for additional discussion on selection of this factor, and sensitivity of results to the choice of CER). As is found elsewhere, the most significant differences among the three cases lie in the modularity of the architecture and the potential for mass production of the system elements. Future studies should examine this and related cases in much greater detail, including more detailed evaluation of the costs for modular systems capable of hosting optical payloads.

In the Farther-Term: Exploration & Development of the Solar System

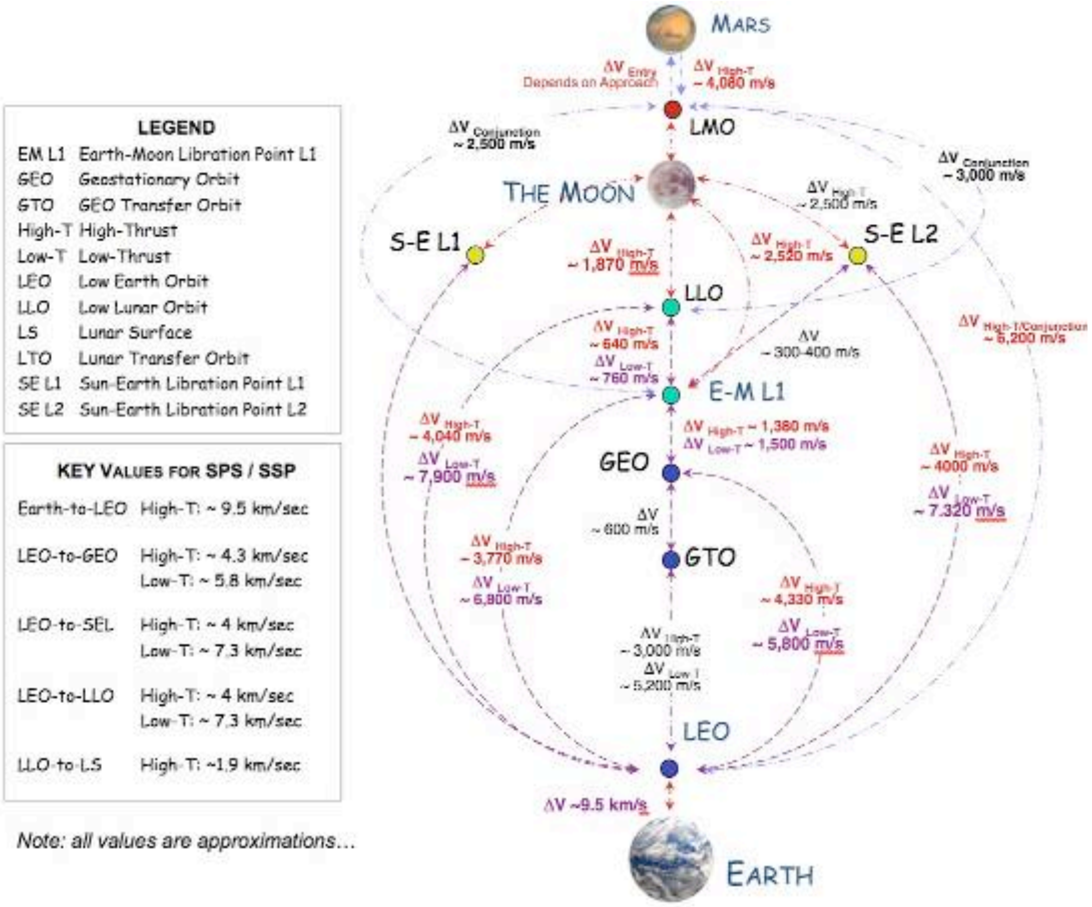
Large-scale affordable power could make a tremendous difference in the future exploration and development of the solar system. Some of the wide range of potential applications a described below.

Space Transportation

Solar Electric Propulsion Systems (SEPS) represent one of the most promising opportunities for application of the SPS-ALPHA technologies and systems that are needed to enable SPS, and of the infrastructure needed to deploy and operate in GEO. These include applications that range from SEPS for orbital transfer vehicles (OTVs) for Earth orbit operations to multi-megawatt (MMW) SEPS for piloted interplanetary missions.

Figure 11-3 presents a “map” of sorts – a diagram of a variety of possible paths for transportation in the Earth-Moon system and the inner Solar System and the energy requirements for each option. There are several general observations that may be made regarding this highly generalized “energetics map.”

Figure 11-3 Space Transport Energy Requirements Diagram



Credit: Artemis Innovation Management Solutions LLC (2013)

First, as we discussed in Chapter 7, the energy requirements (measured in units of "meters per second" in the figure) change significantly depending on the technology. They increase by roughly 70%-90% when the propulsion concept shifts from high-thrust / short duration firing options (such as high-energy cryogenic propulsion) to low-thrust / long-firing options (such as SEPS). This is due to the increase in the gravity losses when a vehicle must take longer to move from one orbit to another in a "gravity well." Second, it is interesting to observe that there is a close similarly among several of the propulsion cases in the figure.

In particular, the energy requirements for low thrust transportation for several cases of interest are as follows:

SEPS Transport from LEO to GEO Change in Velocity:

- ~ 4,300 meters/second; this is the primary in-space transportation mission requirement for a GEO-based solar power satellite, such as SPS-ALPHA

SEPS Transport from LEO to Low Lunar Orbit (LLO) Change in Velocity:

- ~ 4,000 meters/second

SEPS Transport from LEO to the Earth-Moon Libration Point L1 (E-M L1) Change in Velocity:

- ~ 3,800 meters/second

SEPS Transport from LLO to Low Mars Orbit (LMO) Change in Velocity:

- ~ 3,000 meters/second

SEPS Transport from E-M L1 to LMO Change in Velocity:

- ~ 2,500 meters/second

The central conclusion that may be taken from these data is that an SPS transportation system capable of moving equipment and logistics from LEO to GEO (at about 4,300 m/s) is also more than capable of achieving all of the other missions listed. As a result, the transportation infrastructure for SPS-ALPHA would also represent a significant advance in future space capabilities of general value for human exploration beyond LEO. Some additional aspects of these options are discussed in paragraphs that follow.

Human Mars Mission (HMM) Applications. Human Mars Mission (HMM) applications of advanced solar electric propulsion can be conceptualized at three scales: (a) relatively low power (e.g., 50-100 kW) SEPS for application in precursor Mars Sample Return (MSR) missions as early precursors to HMM; (b) mid-power (e.g., 500 kW – 1,000 kW class) SEP freighters the pre-position logistics and systems for an HMM at Mars prior to the human crew being launched; or (c) high-power SEP (e.g., 5,000 kW – 10,000 kW class) SEP crew-carrying interplanetary vehicles.

There are a number of different systems concepts for high-power solar electric propulsion (SEP) systems that could support both SSP transportation (LEO to GEO) and HMM applications (e.g., E-M L1 to LMO). Both of the concepts illustrated are highly modular SEP vehicles that incorporate the design approaches discussed elsewhere in this report. More monolithic vehicle architectures are typically considered and have been examined extensively. However, modular approaches should be capable of realizing much more affordable solutions.

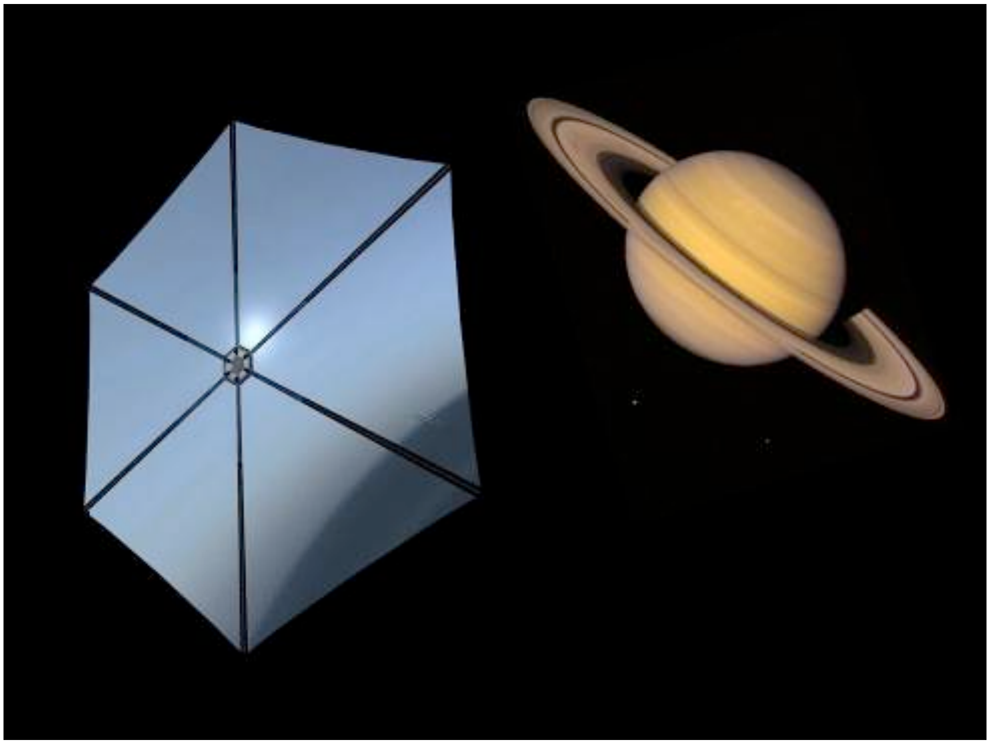
Outer Planet / Deep Space Robotic Missions

For outer planet operations, the solar intensity is too faint to conveniently allow solar energy to be used for spacecraft beyond the orbit of Jupiter. However, at Earth orbit and throughout the inner Solar System, SSP technologies might be used very effectively to deliver high capacity, high power SEP transportation for robotic missions to the outer planets or other deep space destinations. As indicated above, advanced SSP technology SEP stages will be more than capable of sending robots at high speeds to deep space. In such cases, power at the destination would likely be provided by radioisotope energy sources[7] or small space reactor power systems.

Future studies should examine this case in much greater detail, including evaluation of the costs and technology challenges for ancillary systems (such as robotics ISAAC), particularly when operating at remote locations. In addition, the potential for re-use of SPS-ALPHA systems (e.g., the PACA) in future space transportation applications should be examined.

Solar Sails / Spacecraft for Outer Planet / Deep Space Robotic Missions. As illustrated in Figure 11-4, in addition to the types of robotic mission described above, SPS-ALPHA reflector assemblies (including the HexBus) may be able to be used as a solar sail for outer planet or other deep space missions. A good example of this type of configuration (with additional functionality, such as thin-film PV integrated into the solar sail) is the 2011 JAXA IKAROS mission.[8]

Figure 11-4 Illustration of an Outer Planet Solar Sail Mission
Using the SPS-ALPHA Solar Reflector Assembly



Surface Power

Another promising market – beyond that of space transportation – is that of delivering power to operations on the surface of the Moon, Mars, near-Earth and main belt asteroids, or even the moons of the Outer Planets. As an example: one interesting potential option for this class of space applications is the delivery of low-cost solar energy to the Moon during its 14-day night or to regions of the moon that are permanently shadowed at the lunar poles. Such operations would typically require from multiple tens of kilowatts up to hundreds of kilowatts or more power, such as to power in situ resource utilization (ISRU) operations. The economics of lunar power will depend greatly on the details involved; however, three potential cases have been identified, including:

> Case 1: Lunar Surface-based SPS-ALPHA elements (LS-ALPHA), involving point-to-point WPT for systems on the lunar surface, but in shadow

- In this case, WPT transmission would range from 11 to 30 km

Case 2: Lunar Orbit Based SPS-ALPHA (LO-ALPHA), involving power from an elliptical orbiting or pole-sitting small-scale SPS for systems on the surface, in shadowed locations, or during the lunar night

- In this case, WPT transmission ranges would typically be on order 5,000-10,000 km

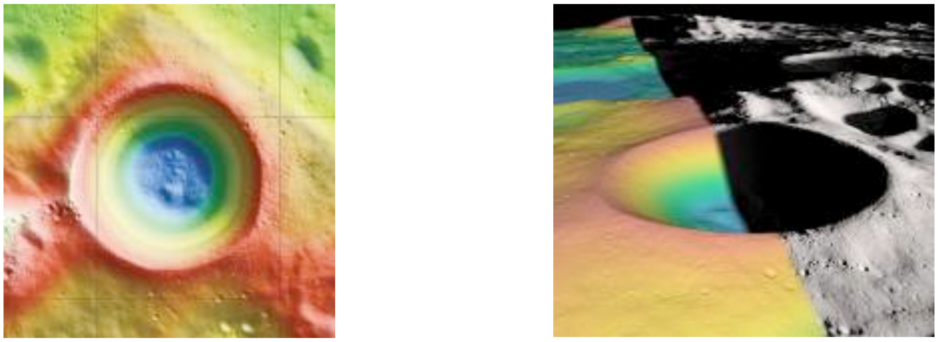
Case 3: EM L1 SPS-ALPHA, involving power from an SPS at the Earth-Moon L1 Libration Point to systems on the lunar surface during lunar night.

- In this case, WPT transmission would be over ~61,000 km

Of these three options, Case 1 ("LS-ALPHA") appears to be nearer-term, and was examined in greater detail as a part of the recent NIAC study.

LS-ALPHA Case Study. In this case, one or more small-scale versions of the SPS-ALPHA primary array would be deployed at locations that are almost always illuminated. These small-scale space solar power systems would be set up in an array perpendicular to the surface, and facing an area of interest that is permanently in shadow. As a "mini-Case Study" conducted during the NIAC project, Shackleton Crater was chosen as a potential location for a surface version of SPS-ALPHA (aka, Lunar Surface ALPHA or "LS-ALPHA"). As shown in Figure 11-5 (from NASA Lunar Reconnaissance Orbiter, LRO data), Shackleton is an impact crater that is located almost exactly at the south pole of the Moon. Figure 11-6 illustrates a potential approach to an LS-ALPHA that could deliver power to systems on the shadowed floor of the crater.

Figure 11-5 Images of Shackleton Crater at the Moon's South Pole

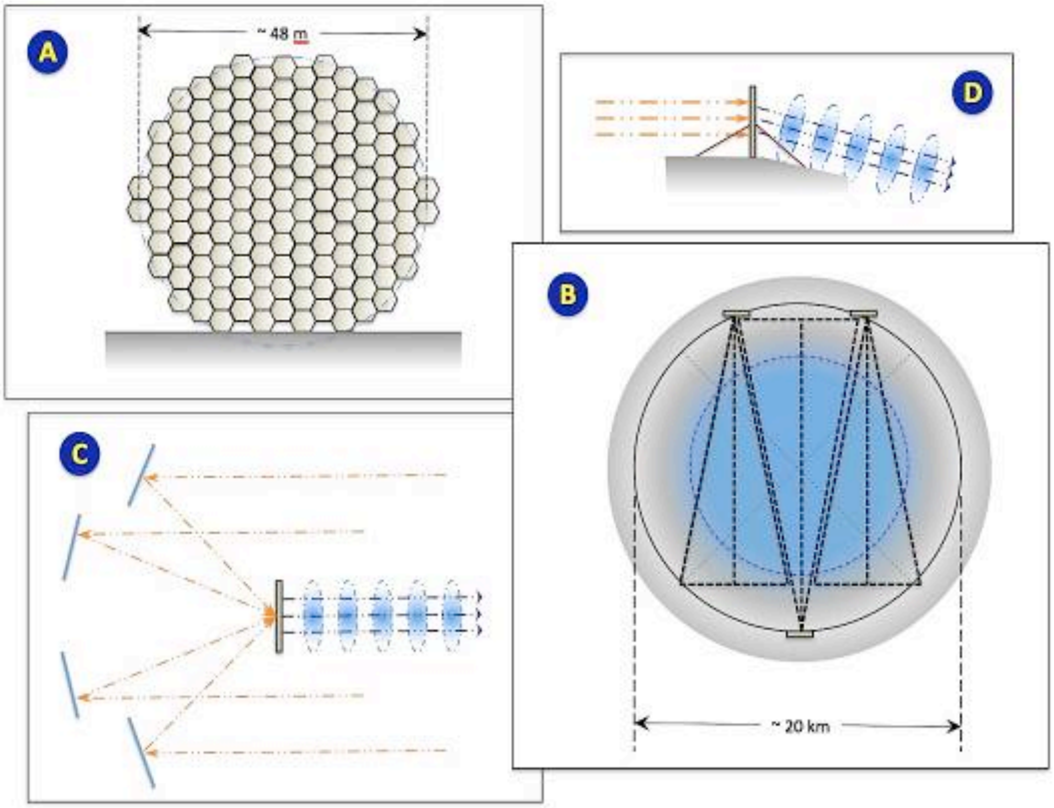


Credit for the Image on the Left: NASA/Zuber, M.T. et al., Nature, 2012

The rim of the crater is exposed to sunlight almost continuously, while the interior of the crater, particularly at the center, is perpetually in shadow. During recent years, it has been shown that the very low temperatures inside the crater operates as a cold trap that captures by freezing volatiles delivered by comet impacts on the Moon

In Figure 11-6, Point A provides a notional view of a surface-based version of the SPS-ALPHA primary array, sized (assuming 4 m diameter HexBus segments) with a total diameter of approximately 50 meters.

Figure 11-6 Concept for a Lunar Surface Version of SPS-ALPHA ("LS-ALPHA")



As in the case of the space-based SPS-ALPHA concept, the elements of this array would comprise: (1) HexBus units, (2) SPG modules, (3) WPT Modules, and (4) Interconnects. The overall array would require robotic assembly (modified versions of the robotics described in Chapter 5 are assumed). Point B provides an overview of the concept, illustrating how several, relatively small diameter SPS-ALPHA type primary arrays could deliver power to almost all the permanently shadowed region at the base of the crater. The illustration shows three arrays, each with a scanning angle of ± 15° from the centerline of the primary array. In this approach, no moving parts would be required at the array.[9] Point C illustrates the idea of using steerable reflectors (heliostats) to ensure that the back plane of the primary array is illuminated constantly. An alternative approach would be to place additional arrays so that one of the arrays would be always be illuminated during the 28-day lunar day-night cycle. Point D provides a side view of the concept, illustrating how the phased array would direct microwave energy into the crater to be received by systems in the permanently shadowed region.

A system of this type was demonstrated by Kobe University (Prof. N. Kaya) in 2009 at the SPS 2009 conference at the Ontario Science Center (OSC) in Toronto, Canada with sponsorship from SPACE Canada. See Figure 11-7 for a photograph of this system, which beamed power at 2.45 GHz to a moving robotic vehicle using a retrodirective phased array with a scanning angle of approximately ±15°. Although small scale, the Kobe University test proved the technologies required for a system of this type.

Figure 11-7 Photo of a Kobe University Demonstration of WPT
at the SPS 2009 Conference in Toronto, Canada

In the case examined, a system similar to a proposed SPS-ALPHA Pilot Plant, generating approximately 500 watts of microwave power per square meter of array, would have an output power of roughly 900 kW for a single array from some 180 panels (each with a mass of approximately 100 kg). For a three-transmitter case (such as is shown in Figure 11-6, Point B), the total RF power generated would be almost 3 MW using some 540 panels. Such a system could deliver (very roughly) about 15-30 W/m^2 to receiver systems at the center of the crater, with the total power received depending on the size and efficiency of the receiver. For example, a moving robotic system with receiver of 10 m^2 in area and an efficiency of 80% would have in on-board power of 120-240 W. Note that this power could be received simultaneously by any number of independent systems within an area of roughly 100,000 m^2 or periodically by any system within the scanning range of the three-unit transmitter array.

For LS-ALPHA panels consistent with the SPS-ALPHA Pilot Plant (which would involve approximately 3,500-7,000 primary array panels), a rough estimate of the cost of an additional 540 panels would be approximately $50,000 per panel, for a total hardware cost of roughly $30M (including only the primary array panels). In the case of the LS-ALPHA application, the cost of electricity will of course depend on how much of the energy delivered by WPT is utilized. For example, in the case of 50 rovers, each using 240 W, and a single central ISRU processor (e.g., producing LOX and LH_2 for fuel) utilizing 50 kW, the total power utilized would be roughly 60 kW and the cost of electricity (over a ten year lifetime) would be roughly $6 per kW-hr. Although high compared to terrestrial energy costs, this would be a significant improvement over conventional space power approaches. By way of comparison, an RTG costing $30 M and producing 200 W would deliver for a single rover a cost of electricity over the same period at a hardware cost of approximately $1,600-$1,800 per kW-hr.

Of course, the cost of landing LS-ALPHA components on the lunar surface are not included above, and the assumption that assembly on the lunar surface can be implemented using robotics similar to or the same as those used for in-space SPS assembly is unproven. Additional study is needed to conduct a rigorous analysis of alternatives (AoA) to compare this concept and others for delivering power to lunar polar operations. The objective of the above “mini-case study” was to illustrate how the system elements of the SPS-ALPHA architecture might be use for diverse non-SPS applications, including lunar surface power.

Small Bodies and Space Resources Development. One ambitious set of space objectives that spans the spectrum from civil space missions to commercial space development involves the exploration and development of the resources of space, in particular those to be found in the small bodies of the Solar System. Missions to first examine and later to rendezvous with – and even redirect the trajectory of – such Near Earth Objects (NEOs) have been mentioned in discussions by leaders in both government and industry during the past several years.[10] These concepts are still controversial; however, the threat posed by possible impacts on Earth is clear: the probability may be low, but the consequences could be enormous.

Space Solar Power will certainly be enabling for missions of this type. The availability of substantial power and the use of advanced SEP propulsion systems have figured prominently in these discussions. And, in the farther term, space resources derived from asteroids and other small bodies must be processed to fabricate consumables and system elements ranging from simple structures to more complex objects.

This is one area in which a potential space mission application intersects with possible future requirements of SPS-ALPHA itself. As we discussed in Chapter 8 (concerning in-space operations), the use of space resources might well prove to be a cost-effective substitute for logistics and spare parts transported from Earth.

Security-Related Applications

Large apertures of various sorts would be of value for security space missions, including large and high-power communications satellites, radarsats, and other Earth observing missions. Moreover, recent studies (e.g., for DOD NSSO) have also concluded that the development of SSP systems and technologies, including SPS, would significantly benefit the security of the U.S. and its allies. Not only would space systems benefit, but the delivery of assured, affordable power to operations, markets, and allies would have significant advantages.[11] (These "premium niche markets" on Earth are discussed in Chapter 11.)

Summary Observations

As we have seen in this Chapter, many types of space applications and market opportunities would benefit from – or be enabled by –large, low-cost Space Solar Power Systems such as those involved in the SPS-ALPHA concept. Table 11-1 on the page following summarizes civil and other government space missions as well as commercial space applications.

In the 1970s, the emphasis in joint DOE-NASA studies was entirely on delivering SPS power to terrestrial markets in the US. By the late 1990s, that emphasis had shifted; the roadmap defined by NASA's SERT Program (discussed in Chapter 3) framed SSP development in terms of a series of systems development stages where each stage demonstrated an increasing level of power on the path to full-scale Solar Power Satellites. Each stage in the 1999-2000 Space Solar Power roadmap also involved prospective spin-offs for NASA applications. The hyper-modular approach of SPS-ALPHA enables that evolution to go still further: systems, technologies, and infrastructures developed for SSP can be applied in civil, commercial, exploratory, and other space missions well before the deployment of the first commercial SPS. The various systems involved in the supporting infrastructure and related technologies (including low-cost launch and transformational new in-space operations capabilities) will also be important.

We'll turn now to the next important question: what is the potential for Space Solar Power in terrestrial energy markets?

Table 11-1 Summary of Potential Space Missions and Applications of SPS-ALPHA

Time Frame	Venue for Application	Type of Application	Application
Nearer-Term (5-10 yrs)	Terrestrial	Technologies	Point-to-Point Wireless Power Transmission
	Low Earth Orbit	Systems	LEO Communications Satellites Constellations (Large Aperture, High Power, Multiple Spot)
			Robotic Servicing or Debris Mitigation in LEO
	Geostationary Earth Orbit	Systems	GEO Communications Satellites (Large Aperture, High Power)
			GEO Earth Remote Sensing Satellites (Large Aperture, High Power)
		Supporting Infrastructure	LEO-GEO Transport for GEO Satellites
			Robotic Servicing for Satellites in GEO
Mid-Term* (10-20 yrs)	LEO (or other orbits)	Systems	Large Optical Communications Terminal
	Geostationary Earth Orbit	Systems	As above, continuing
	Earth-Moon System and Vicinity	Systems	Lunar Surface Power Systems / Wireless Power Transmission (Point-to-Point)
		Supporting Infrastructure	LEO-LLO Transport for Lunar Missions (Cargo missions for human exploration, surface operations, etc.)
			LEO-Target Transport for Near-Earth Asteroid and Libration Point Missions (Cargo missions for human exploration, surface ops, etc.)
	Beyond the Earth-Moon System	Supporting Infrastructure	Transportation for robotic exploration missions (inner solar system and beyond)
		Systems	Space Resources Development (Small Bodies)
Far-Term* (20-30 yrs)	Geostationary Earth Orbit	Systems	As above, Continuing
	Earth-Moon System and Vicinity	Systems	Orbital Systems (Lunar or Libration Point) SPS for Lunar Surface Power
Very Far-Term* (>30 years)	Geostationary Earth Orbit	Systems	As above, continuing
	Mars and Vicinity	Systems	Mars Orbit SPS for Surface Power

Time Frame	Venue for Application	Type of Application	Application
		Supporting Infrastructure	Transport for Human Mars Mission (Cargo missions for human exploration, surface operations, etc.)
** Note: In this table potential applications are indicated on in the first timeframe when they might occur; for the sake of clarity they are generally not repeated in later timeframes during which they might also be possible (except in the case of GEO applications)*			

[11-1] See: http://www.bbc.co.uk/news/technology-17510101.

[11-2] The total power of the solar arrays on the ISS is greater; however, roughly 1/3 of each orbit is spent in Earth's shadow, during which time power is supplied by an onboard system of batteries providing energy storage. The solar arrays recharge those batteries as well as providing power to the ISS modules during the sunlit portion of each orbit.

[11-3] It will be interesting to see if the advent of new heavy lift vehicles, such as the "Falcon Heavy" proposed by the commercial space company Space Exploration Technologies, Inc. ("SpaceX"), will change this situation.

[11-4] Note: Case 2, the smallest GEO "CommSat-ALPHA," includes mass for launch of the robotic in-space assembly and construction systems as well as the required space structures and reflectors, etc.

[11-5] Although the conventional architecture spacecraft considered here is entirely notional (and does not reflect any specific spacecraft), the scaling and other data are not inconsistent with the recent JAXA ETS-VIII spacecraft.

[11-6] See: Hurd, William J., eet al, "Exo-atmospheric telescopes for Deep Space Optical Communications," (2006 IEEE Aerospace Conference, Big Sky, MT) March 4-11, 2006.

[11-7] These often involve RTGs (radioisotope thermoelectric generators), but might in future involve more advanced systems such as DIPS (Dynamic Isotope Power Systems).

[11-8] See: see: http://www.jspec.jaxa.jp/e/activity/ikaros.html, and http://www.jaxa.jp/projects/sat/ikaros/index_e.html.

[11-9] Another approach could involve using tracking heliostats directly to reflect sunlight to systems at the base of the crater. However, this would involve active tracking of roving vehicles and could be affected by dust arising from ISRU operations. This option should be examined in a future study.

[11-10] See: http://articles.washingtonpost.com/2013-07-20/national/40691732_1_asteroid-initiative-capture-mission-house-committee. Also, for information on commercial ventures, see: www.planetaryresources.com/, and www.deepspaceindustries.com/.

[11-11] See: http://www.nss.org/settlement/ssp/library/final-sbsp-interim-assessment-release-01.pdf

Chapter 12

Terrestrial Energy Markets

> *"Lee DeForest has said in many newspapers and over his signature that it would be possible to transmit the human voice across the Atlantic before many years. Based on these absurd and deliberately misleading statements, the misguided public...has been persuaded to purchase stock in his company..."*
>
> *a U.S. District Attorney (1913)*
> *prosecuting American inventor Lee DeForest for selling stock "fraudulently" through the mail for his Radio Telephone Company*

Introduction

SPS-ALPHA has the potential to make possible not only a range of ambitious future space mission applications such as those we discussed in the last Chapter but also the vision of continuously delivering almost limitless solar energy to people on Earth. Since the invention of the concept, expectations regarding the markets that SPS might serve have evolved – just as have technical approaches. From the 1960s through the 1970s, discussions of Solar Power Satellites focused on large baseload power markets in the United States. The total envisioned capacity at that time was for some 60 SPS platforms to deliver 300 GW (at 5 GW per platform) to the same number of dedicated receivers across the US. Naturally enough, during the 1980s and 1990s, international SSP efforts, including those in Japan, Europe, and Canada generally presumed power being delivered into those respective baseload markets. Also, they focused more on SPS technology (e.g., WPT) rather than on end-to-end systems studies. One of the most interesting developments in the study of prospective Space Solar Power economics during the past decade or so has been the emergence of what might be described as "premium niche markets." These relatively small-scale markets for SSP are characterized by several factors, including:

Market demand for power that is largely insensitive to the cost of the power provided (for example, this might be the case if there are legislatively mandated "green energy" requirements that must be satisfied);

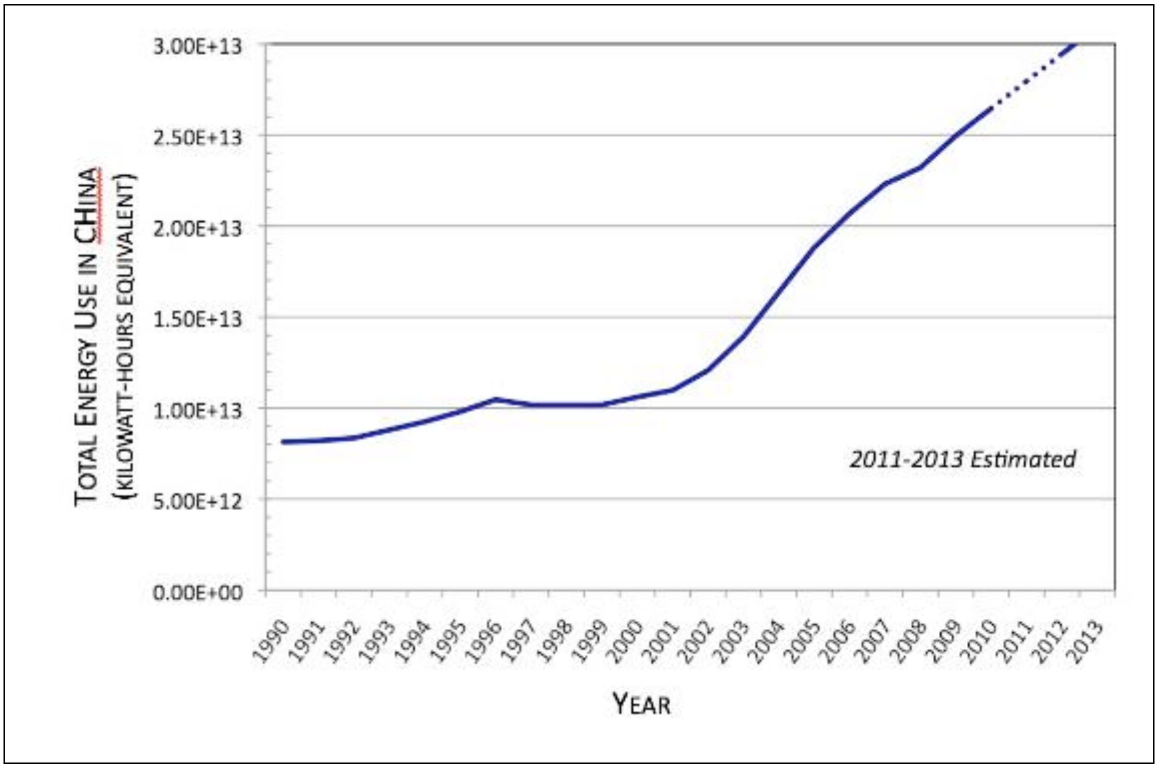
Geographically or otherwise isolated markets where the available sources of energy are quite expensive; and

Markets that are expected to be transient or dangerous, and therefore do not justify investments in more traditional fixed infrastructures (e.g., secure power transmission systems to remote locations).

An example of such a market would be a US (or allied) military “forward base” application. These premium markets appear to be global in character and to represent substantial economic potential: they offer prices that far exceed conventional, baseload power markets. We will discuss other examples in just a moment.

Another remarkable development during the past 20 years has been the rapid emergence of robust international markets – particularly China and India, but also other countries in Southeast Asia, sub-Saharan Africa and elsewhere. Figure 12-1 illustrates this with the largest example; it depicts China’s increase in energy use over the period from 1990-2010.[1] Clearly the potential market for SSP is not just in the U.S.

Figure 12-1 Growth in Energy Use in China during 1990-2010



Credit: Artemis Innovation Management Solutions LLC (2013)

A third promising development in SSP economics during the past two decades has been the emergence of the policy goal of reducing CO_2 emissions and concomitantly boosting the deployment of renewable energy systems – including wind, solar, and essentially all other low CO_2 emission power sources. This policy shift has significantly improved the market for all sustainable energy solutions because of the emergence of carbon-reduction motivated economic incentives. As we discussed in Chapter 2, in various countries and even some localities within countries (for example, in the US state of California), governments have instituted policies that promote the early deployment of new energy technologies by offering premium prices for electricity or reduced taxes, or both. In some locations, these are known as “feed-in tariffs”, and can be quite significant in the early years of operations for a new sustainable energy source. (The intermittent nature of wind and solar is a major challenge for utility operators in these markets; a problem that SSP can help solve.)

This Chapter examines a range of promising terrestrial energy market opportunities and continues to develop the business case for Space Solar Power in general and SPS-ALPHA in particular; building on the SPS-ALPHA market assessment conducted as part of the 2011-2012 NIAC Phase 1 project. It summarizes market opportunities for new energy here on Earth, including both "Primary" markets and several likely "Secondary" markets.

For each of these prospective market sectors, several specific prospects are described, including details such as characteristics of current markets, current market prices, and the market forecast for the remainder of this century, including both characteristics and prices. The Chapter concludes with an integrated forecast of SPS-ALPHA markets that will in turn be used to frame the integrated business case for SSP.

The starting point is a quick review of past SPS market and economic studies, including the objectives of those studies, the assumptions that framed them, and their results.

Past SPS Market & Economic Studies

During the 1970s, NASA and the then newly-created Department of Energy (DOE) conducted SPS studies that focused on technical design issues and assumed a very top-down, national policy driven market scenario in which power from some 60 satellites would be delivered in 5,000 MW transmissions to 60 ground receiving sites in the US – for a total of some 300 GW total delivered power. The projected cost (initial and operating) of the deployed infrastructure and SPS was divided directly by the total electricity delivered over a number of decades to determine the cost of the electricity produced (stated, of course, in terms such as "dollars per kilowatt-hours"). Following 1980, increasing international activities tended to focus on various technology objectives (including sounding rocket experiments, etc., discussed elsewhere), rather than on systems studies.

The US approach to Solar Power Satellite market analysis changed dramatically beginning in the mid-1990s. From that time, NASA implemented market studies and supported external efforts while DOE participated only in an advisory role. Moreover, these studies extended the market prospects for SPS power to include global markets. The emphasis continued to be on large-scale (GW and greater) baseload markets in the US, but other options such as peaking power were beginning to be discussed, particularly in the context of LEO options such as the SunTower. Since around 1995, the purpose of US SPS market and economic studies was to establish market-driven economic objectives (e.g., a specific price in terms of ¢/kW-hour) that could in turn be used to evaluate various technology and systems design options. During NASA's Fresh Look Study of SSP (1995-1997), economic considerations were closely integrated into architecture-level systems analysis studies. The economic objective established for that study was a goal of some 10¢/kW-hour or less for baseload power (in 1997 dollars).

NASA's SSP Exploratory Research and Technology (SERT) program (1998-2001) sponsored an independent economic assessment of SPS. As it happened, that assessment (implemented by a non-profit organization in Washington, DC, *Resources for the Future*) chose to focus only on the main US baseload market, as had studies in the 1970s. Some of the key assumptions of that assessment were approximately as follows:

> The energy market to be served by SPS will be the US baseload power market (<u>not</u> including Hawaii and Alaska, or the US territories).
>
> The market price that must be achieved for SPS power to be sold would be that of the <u>lowest</u> power price (i.e., consistent with a power generation cost of approximately 5¢/kW-hour).
>
> The return on investment (ROI) for SPS investments must be approximately <u>30%</u> or more (i.e., comparable to that of information technology (IT) companies of the late 1990s).
>
> There would be no explicit incentives for Space Solar Power (i.e., no tax incentives, no loan guarantees, no policy-driven CO_2 reduction objectives, etc.).
>
> And, that the above assumptions would continue to be true for the foreseeable future (i.e., out to several decades from the 2000 timeframe).

Together, these SSP independent market assessment assumptions were equivalent to the extremely challenging requirement that power delivered by SPS must be at the cost of power delivered by existing coal-fired baseload electrical power plants in the continental United States <u>but</u> with financial returns equivalent to the "dot-com bubble." While not unreasonable as goals for the longer term, these market requirements were at the time – and continue to be today – almost impossible for any new energy technology to meet, not just Space Solar Power. These assumptions did not reflect the actual market for sustainable energy during 2000-2015 very well, as we'll discuss in a few pages.

During 2007, a novel set of potential markets for Space Solar Power was introduced in the context of an online study performed for the National Security Space Office (NSSO), a former office with the US Department of Defense. This study raised, for the first time in a systematic way, the idea that there were special markets in remote locations associated with military operations that pay considerably more for electricity than baseload power prices in the US. These so-called "Premium Niche Markets" (PNMs) represented markets in which power up to megawatts might be delivered at prices above $2 per kilowatt-hours – more than 20-times greater than baseload power in the US. While identifying new opportunities, the market perspective of the "Space-based Solar Power" study for the NSSO was nevertheless highly tactical in character.

By contrast, the 2008-2011 International Academy of Astronautics (IAA) study framed yet another very different economic context for its assessment of SSP. At the outset, the participants recognized that the Academy study did not possess the resources to develop a rigorous economic forecast or to integrate economic objectives into a comprehensive end-to-end architecture-level systems analysis study. As a result, the IAA assessment began by defining a set of four strategic global scenarios, and then developed an internally consistent market forecast from that basis. The IAA Scenarios focused on three major areas: population growth; fossil fuels availability and prices; and climate change and related policies. In Chapter 2, we discussed updates to the original IAA scenarios (frame in 2008-2011); this updated set of four strategic Scenarios form the basis for the market assessment discussed in this Chapter.

Another highly important development in the energy marketplace since the Fresh Look Study was reflected in the IAA study results: the emergence of greenhouse gas (GHG) policy-driven economic incentives to stimulate the development of sustainable energy options. As noted above, the major consequences have been the introduction of allowable rate adjustments for "green" energy, known as "Feed-In Tariffs" (FITs), tax adjustments for such sources and other incentives, and related R&D.

All told, the market context for Space Solar Power has changed significantly since the 1970s. The global need for new sustainable energy sources has never been greater and it is only likely to increase further in coming decades. Before turning to the details of the terrestrial energy market opportunities for SSP, it is important to pause for a moment and recall some physical constraints on the locations to which power can be delivered from an SPS in a geostationary Earth orbit (GEO).

Physical Constraints on SPS Energy Markets

As we discussed in Chapter 4, the optimum location for a Solar Power Satellite is at or near a geostationary Earth orbit in which a satellite orbits once every 24 hours – appearing to be fixed in the sky to an observer on the ground. However, it is not possible for a GEO-based satellite (using microwave WPT) to transmit power to all locations even on the surface below. At the equator, there is no problem; however, as the latitude increases (the distance north or south away from the equator), the angle at which the transmission reaches the ground also increases until, at either the north or south poles, the transmission misses the surface below. (The same effect also occurs, of course as the transmission shifts to the east or west.) Figure 12-2 illustrates this effect for three different possible SPS locations in GEO: (a) over sub-Saharan Africa; (b) off the water coast of South America; and (c) over the South Pacific at about the longitude of Japan.

As illustrated, the required area per unit power produced by the receiver will go up with increasing angle away from the point on the equator directly below a GEO-based SPS. The variation is based on the cosine of the angle, along the North-South direction or to the East-West; if North-East, North-West, etc., the increase will be the greatest.

Figure 12-2 View of Earth from GEO Illustrating Accessible SPS Markets*

EUROPE-AFRICA-MIDDLE EAST

View of Earth from a GEO SPS over sub-Saharan Africa. The crossed circle represents the point directly below the hypothetical location of the platform.

(Note: ellipses are not to scale; each ellipse indicates the overall shape of a WPT transmission on the ground at that location, not its size.)

AMERICAS (NORTH-SOUTH)

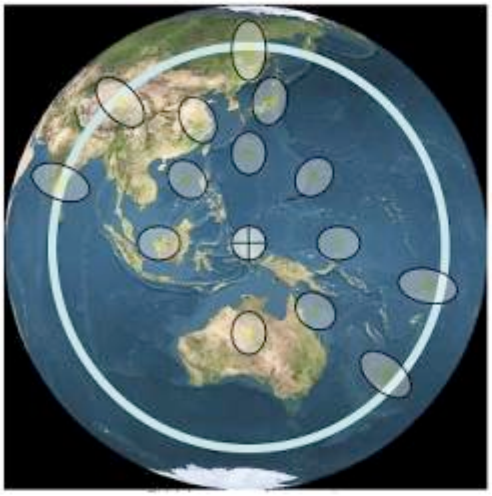
View of Earth from a GEO SPS over off the west coast of South America.

(Note: ellipses are not to scale.)

ASIA-PACIFIC

View of Earth from a GEO SPS over over the South Pacific at about the longitude of Japan.

(Note: ellipses are not to scale.)



Credit: Artemis Innovation Management Solutions LLC (2013)

Also, at higher angles (e.g., about 60° away from directly below the satellite) there will be increasingly important losses due to power transmission transit through the atmosphere. (This is much worse for lasers than it would be for microwave power transmissions.) For microwave WPT, this should not have a significant effect, even up to quite a large angle away from the nadir-point on the equator below the platform (say, up to about 45-50 degrees). The cost of the rectenna may be expected to be about 5% of the total cost of the system; a notional doubling of that cost (worst case) is not a huge increase in the total cost. As a result, there is an advantage for countries on the equator and directly below the orbital location of an SPS, but it is not a large one.

The most attractive sites for rectennas based in larger open areas at the equator are probably in Africa. India and China are both entirely north of the equator, of course; however, all of the land area of India and the majority of the land area of China are below 45 degrees north latitude; the same is true for most of the US and of Europe. Also, WPT receivers may be located offshore (albeit at higher cost), just as is the case for wind power. As a result, almost *all* countries are perfectly accessible as possible sites for a rectenna (although most are not quite as good as equatorial Africa).

Since most of humanity lives below 45° North or South latitude, these constraints would not be a major issue for SPS terrestrial energy market opportunities; several GEO-based Solar Power Satellites would have the potential to deliver power effectively to more than 90% of humanity.

Primary Markets

The primary markets for SPS-ALPHA within the global commercial energy marketplace include: (1) baseload power sales; (2) peak power sales; (3) premium niche power market sales; and (4) sales of power to enable local production of selected high-value chemical products [including fuels, fertilizers, and interim chemical feed-stocks (e.g., “synthesis gas”, a.k.a. “Syngas”)].[2] Still another potential future market is that of fresh water production – particularly in areas affected by the depletion of historically reliable river systems, snow packs, and/or aquifers. In addition, as we’ve discussed, recent policies regarding greenhouse gas emissions have created market opportunities.

Commercial Baseload Power

The commercial baseload power market is enormous and growing; it is a fully global market that comprises all countries. It involves a diverse array of market types, ranging from deregulated commercial markets with public oversight (as in the US) to fully regulated and/or government owned national energy company markets.

Market Characteristics. For conventional baseload sources, power is usually acquired from large power plants – primarily coal, hydroelectric or natural gas turbine or nuclear installations – that typically deliver from 100 MW-1,000 MW of power. During the entire year of 2008, global use of electricity was about 20,000 terawatt-hours (or 20,000,000,000,000 kW-hours), while total energy use (including combustion of fuels for transportation, heating, power generation, etc.,) was many times greater, reaching approximately 140,000,000 TW-hours.

Still, however great the current global demand for energy, it remains only a tiny fraction of what could be available. 2008 electricity production represented only 11% of the solar energy Earth's surface receives in one hour (which is 174,000 TW-hrs). In 2008, the sources of electricity were fossil fuels at 67%, renewable energy at 18%, and nuclear power at 13% of the total. The majority of fossil fuel combustion for electricity was of coal and gas, while oil (much more expensive) represented only 5.5% and was used largely in special niche and/or isolated markets – such as the US State of Hawaii. Hydroelectric power represented 92% of renewable energy, followed by wind at 6% and geothermal at 1.8%, Solar photovoltaic was 0.06% and solar thermal was 0.004%.

The use of energy per person varies widely from country to country and from region to region, as does the efficiency with which energy is used to produce goods and services [i.e., the "energy per unit of Gross Domestic Product (GDP)" varies significantly]. However, during the past 40 years, the consumption of electrical power *per capita* has risen steadily while the global population has also increased – resulting in accelerating growth in the use of electrical power that is projected to continue for the remainder of this century. The prices paid for electricity also vary greatly from country to country.

Market Prices. Wholesale and retail prices for baseload power generated by traditional plants vary greatly depending on the location, access to specific resources (for example, water in a lake for a hydropower plant), and other market factors. See Table 12-1 for some recent examples of retail prices for electricity in various regions around the world. A couple of notes must be made about the data in the table. First, it is evident from these data that, in many markets, the prices paid at the retail level by consumers are subsidized to a greater or lesser extent by the governments involved. (For example, given the similarity in prices paid in Japan and the Philippines in the Asia-Pacific region, there is no evident reason why electricity prices paid in Indonesia should be on 1/10 as much. It seems likely that prices in Indonesia are significantly subsidized for public policy reasons.)

Table 12-1 Electricity Retail Prices in Various Countries Around the World[3]

REGION	COUNTRY	LOWEST PRICE (US cents per kW-hr)	MID-POINT PRICE (US cents per kW-hr)	HIGHEST PRICE (US cents per kW-hr)
Americas	US: Average		~10 ¢ / kWh	
Americas	US: California	12.5 ¢ / kWh	~25 ¢ / kWh	40 ¢ / kWh
Americas	US: New England		~14 ¢ / kWh	
Americas	Canada	6 ¢ / kWh	~6 ¢ / kWh	7 ¢ / kWh
Americas	Brazil	7 ¢ / kWh	~13 ¢ / kWh	20 ¢ / kWh
Americas	Mexcio	5 ¢ / kWh	~12 ¢ / kWh	19 ¢ / kWh
Americas	Bahamas	35 ¢ / kWh	~37 ¢ / kWh	38 ¢ / kWh
Asia-Pacfic	Australia		~17 ¢ / kWh	
Asia-Pacific	China		~7 ¢ / kWh	
Asia-Pacfic	India	3 ¢ / kWh	~5 ¢ / kWh	8 ¢ / kWh
Asia-Pacific	Indonesia	2 ¢ / kWh	~4 ¢ / kWh	6 ¢ / kWh
Asia-Pacific	Japan	21 ¢ / kWh	~25 ¢ / kWh	29 ¢ / kWh
Asia-Pacific	Philippines	22 ¢ / kWh	~23 ¢ / kWh	25 ¢ / kWh
Asia-Pacific	US: Hawaii		~34 ¢ / kWh	
Europe-Africa	France		~17 ¢ / kWh	
Europe-Africa	Germany		~27 ¢ / kWh	
Europe-Africa	Italy		~33 ¢ / kWh	
Europe-Africa	Saudi Arabia		~1 ¢ / kWh	

Also, depending on the policies of the involved government, the actual electricity consumed represents a mix of many types of generation and a wide range of production costs. For example, in Germany the mid-point retail price is roughly 27¢ per kW-hour; however, the feed-in-tariff for solar power (i.e., the wholesale price) ranges from about 18¢ to 24¢ per kW-hour, and for other sources differs significantly. In China, up until 2011, the wholesale price for solar power was subsidized at around 18¢ per kW-hour, even though the retail price of electricity is set at 7¢ per kilowatt-hour. Similarly, in Japan the mid-point retail price for electricity is about 25¢ per kW-hour; however, the country's feed-in tariff for solar power is roughly 42¢ per kW-hour (at May 2013 exchange rates).[4]

Depending on the technology involved, typical costs for electricity range in many markets (including most of the US) from about 5¢ to 10¢ per kWh; however, in specialized markets (such as remote regions or islands), the cost of baseload power can be considerably greater, reaching 10¢ to 20¢ per kWh or more. (See the discussion below concerning the allowable wholesale energy price during the introduction of a novel renewable energy technology.) In addition, the price for energy may vary greatly depending on how much electricity is used in a given billing period.

Market Forecast. During the remainder of this century, the use of commercial baseload power is forecast to grow dramatically in all regions of the globe with the exception of countries in the OECD (Organization of Economic Cooperation and Development), such as the US, Japan, France, and others. In these developed countries, use of electrical power is also forecast to increase but much more slowly, due to slower increases in populations, lower rates of economic growth, and ongoing improvements in the efficiency of energy use per unit GDP. In Chapter 2, Table 2-1 presented an integrated view of various electricity related forecasts summarized by the recent International Academy of Astronautics (IAA) study of SSP by the including projections of global population growth and annual global energy use through 2100. The key aspect of this forecast is that the global demand for electricity is projected to approximately quadruple between 2010 and 2100. Hence, there is a vast potential market for Space Solar Power during the remainder of this century – if the prices for SSP are competitive with terrestrial sources in relevant markets. And, as we saw previously, at least in selected markets around the globe, wholesale prices higher than 10¢ per kilowatt-hour are currently being paid.

In the longer term, there is considerable uncertainty regarding the evolution of the primary commercial baseload power market. This uncertainty is embodied in the several strategic Scenarios we discussed in Chapter 2: will climate change become a disastrous issue and soon? Will fossil fuels become depleted sooner than expected? Will sustainable energy technology investments be pursued more aggressively than at present? Depending on the answers to these questions, the longer term forecast will vary greatly. At the end of this Chapter, Table 12-2 presents a set of detailed forecasts for baseload commercial power based on the two Scenarios from Chapter 2 that "bracket" the range of variations.

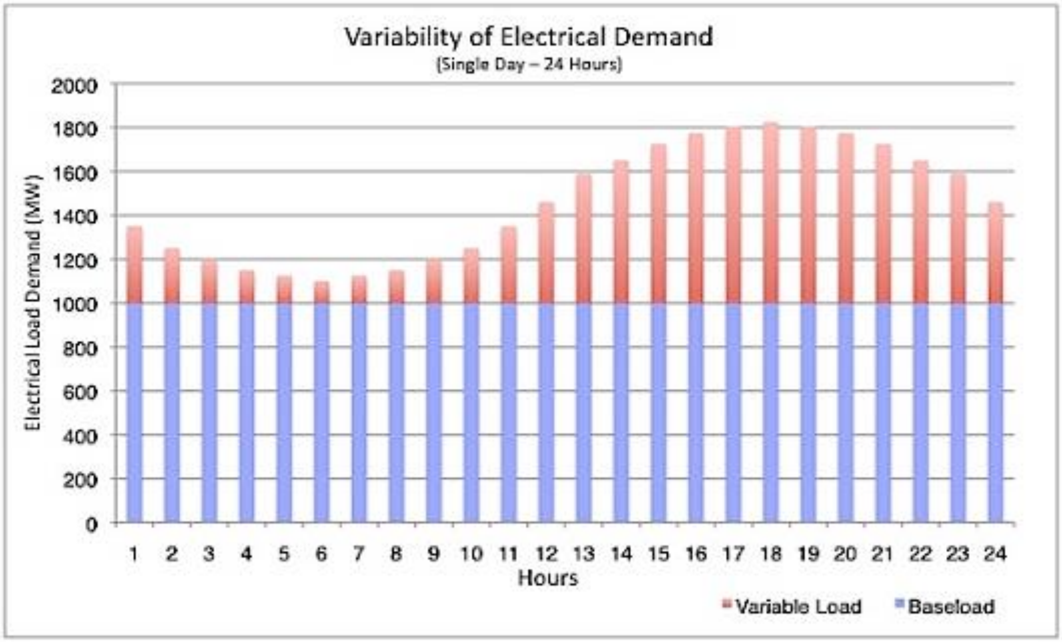
Commercial Intermediate & Peaking Power

There is a global market for commercial intermediate & peaking power that matches closely the commercial baseload power market, comprising the same array of countries and market types, ranging from fully deregulated commercial markets (as in the US) to fully regulated and/or national energy company markets.

Market Characteristics. Unlike the market for baseload power, the demand for commercial intermediate power and peak power changes on an hourly basis during each day (as well as incorporating day to day variations based on the weather, and longer term variations based on the season of the year). Figure 12-2 presents a typical urban market diurnal (day-night) cycle for commercial intermediate & peaking power demand on an hourly basis. (This figure does not reflect a specific locality but follows the general demand curve that might be expected in the middle state of the US in summer.) The figure illustrates (a) the baseload power level below which demand does not drop during a 24-hour period, and (b) the variable load power level, which is shown to peak in the later part of the afternoon during a typical summer day.

As shown in the figure, the peak power demand occurs during a relatively small fraction of each day and can be difficult to anticipate in detail more than 5-10 days in advance (corresponding to the timeframe for accurate weather forecasting). Intermediate power demand occurs during a much longer period of time than peak power demand, and typically occurs during daylight hours when commercial power use increases (particularly for air conditioning during the summer months). The figure is highly idealized; actual demand fluctuates greatly season-by-season, day-by-day and hour-by-hour, with occasional sharp spikes.

Figure 12-2 Typical Daily Variation in Power Demand



Credit: Artemis Innovation Management Solutions LLC (2011)

Market Prices. The wholesale and retail prices for commercial intermediate power and peak power generated from whatever source can vary widely depending on the location, immediate access to power generating capacity, seasonal considerations, and other market factors. In North America, peak power costs have been estimated to be as high as \$1.00 - \$1.30 per kWh for a period of as much as six hours.

Market Forecast. On an individual market basis, the demand for commercial intermediate and peak power may be forecast to scale (albeit locally) with increasing commercial baseload power demand, and to change globally with the scope of total energy utilization. In the far term, the basic character of this market can be expected to remain unchanged; for purposes of this discussion, that translates into prices that are proportionately greater than local baseload power.

Sustainable Energy Sources

During the past 20 years, the increasing international scientific consensus that greenhouse gas emissions are resulting in global climate change has been compounded by increasing concerns regarding energy security in the context of surging demand for energy in the developing world (discussed previously). Based on these developments, the "sustainable energy sources" market sector may be expected to see several policy-driven government investments or other supports (e.g., tax breaks) to encourage the development, deployment, and commercialization of new, low-carbon energy systems.

Market Characteristics. Intermittent availability (a.k.a., "variability") has been a key characteristic of traditional sustainable energy projects (with the exception of hydroelectric power), particularly solar and wind. Another has been the requirement for grid upgrades (e.g., to so-called "smart grids"), and limitations on the percentage of renewable energy allowed in the power mix. As we've discussed, a key feature of numerous recent international sustainable energy projects has relied on a market incentive known as the "Feed-In Tariff" (FIT). FITs have been largely responsible for the recent strong growth in solar power in Spain and Germany and in wind power for Denmark.

Market Prices. In general, government policy-driven market incentives for the introduction of new sustainable energy sources involve (a) guaranteed access to markets; (b) above conventional source prices (e.g., up to 50¢/kWh) and (c) long-term contracts (e.g., for up to 10, 15 or 20 years). The total targeted percentage contribution to the energy mix from sustainable energy sources may be as great as 20% or more.

Market Forecast. Sustainable energy sources are forecast to continue as a stable and growing portion of the total global energy mix, with continuing policy incentives in various regions and countries similar to those that have been in place during the past 10-15 years in specific locations. As a key part of the SPS-ALPHA market model, it is assumed – just as has been the case for other new sustainable energy technologies during the past 20 years – that Feed-In Tariff (FIT) or other financial incentives will be available to support the initial introduction of SPS-ALPHA power, particularly for the commercial baseload market. In particular, the projection for the SPS-ALPHA market assessment is modeled on the German government's 2000-2010 FIT for solar power, which included three stages:

(1) Years 0-8 FIT up to ~ 40¢-50¢ per kWh;

(2) Years 9-13; FIT up to ~ 20¢-25¢ per kWh; and,

(3) Years 14-20 FIT up to ~ 15¢-20¢ per kWh.

As has been seen with various technologies, beyond the first 20 years, energy from SPS-ALPHA should be able to deliver baseload power at competitive prices without incentives.

Secondary Markets: Energy

In addition to the primary market discussed above (i.e., global baseload power), there are several secondary terrestrial markets that SPS-ALPHA may also serve; chief among these are (1) commercial premium niche power markets; (2) national security power markets; (3) markets for power to be used to drive production of high-value chemical products; and (4) point-to-point power transmission to niche markets.

Commercial Premium Power (PP) Markets

Commercial premium power markets are entirely dependent on the specifics of the location and situation; however, they can occur in a wide variety of locations around the globe. The wholesale and retail prices for PP generated from whatever source can vary widely depending on the location, local power generating capacity, seasonal considerations, and other market factors. Examples include power for geographically remote locations and islands, as well as power during emergency situations. In North America, isolated northern areas in Canada, for example, experience energy costs estimated as high as 50¢ per kWh for power from imported diesel fuel and generators. In such cases, the demand comes from modest-size communities (e.g., about 1,000 inhabitants) or commercial operations, with total power requirements of up to some 10-20 MW. In the longer term, such markets will most likely continue to exist, and perhaps increase in number and in size during the remainder of the coming century.

National Security Premium Niche Power Markets

National security-related premium niche power markets were first identified during the 2007 study of Space Solar Power for defense applications that was conducted for the US National Security Space Office (NSSO). These markets emerge due to military operations or because of a requirement for short-term emergency operations (e.g., to support relief operations in the aftermath of a major national disaster, such as an earthquake, a tsunami, etc.). These markets are hard to predict with precision, and the duration of power demand will typically be of finite duration (e.g., less than one year as a minimum, up to 3-10 years as a maximum).

National security-related demand has been identified as typically ranging from 1 MW to 10 MW at various forward operating bases at remote, typically hostile or otherwise difficult environments. Prices paid for energy to meet the needs of these markets can range as high as \$2.00 to \$3.00 per kilowatt-hour. During the remainder of this century, it is anticipated that such markets will continue to emerge, require power for some period of time (e.g., up to 10 years), and then vanish as operation move another location.

Energy for Production of High-Value Chemical Products

In future, one such high-value chemical product (HVCP) may increasingly be fuels (e.g., Methanol or synthetic petroleum) as well as fertilizers. The use of Space Solar Power to drive such thermochemical processing could prove to be a highly valuable undertaking, particularly while the price of a feedstock such as natural gas remains low and the price of liquid fuels such as gasoline or aviation fuel remains high. This is a good topic for future study, but a detailed consideration of this opportunity is beyond the scope of our current discussion.

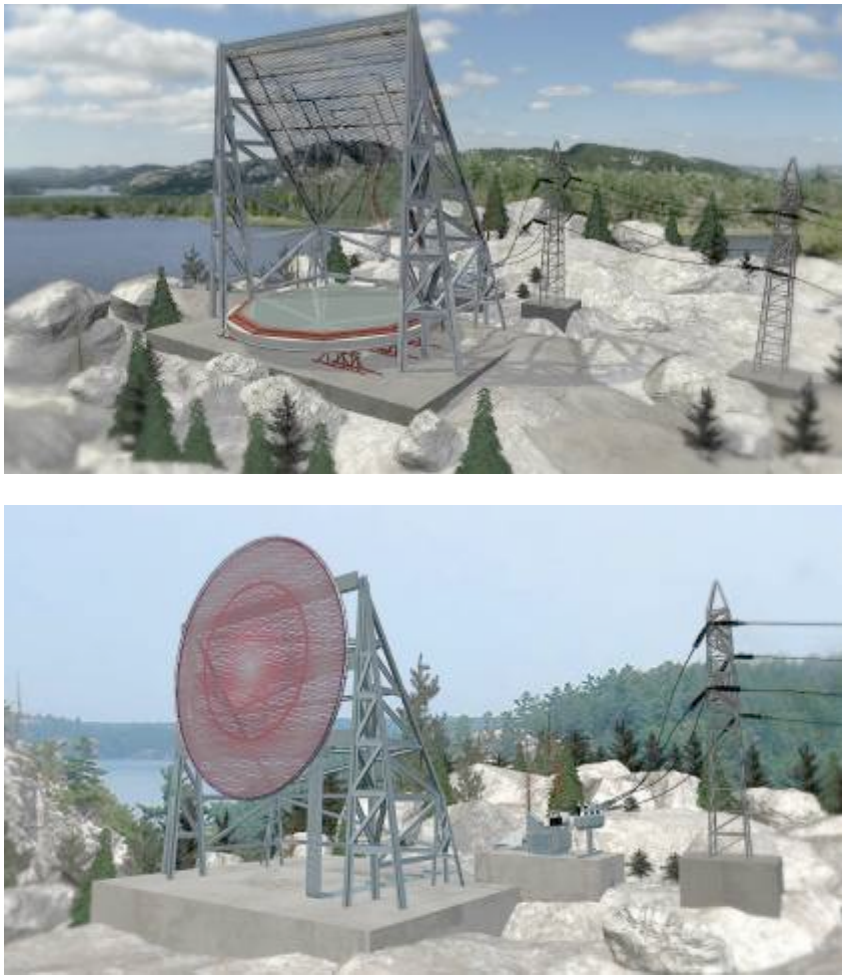
Point-to-Point Power Transmission in Niche Markets

There is one more secondary market that should be mentioned. A number of studies performed over the past 20-plus years have examined the potential for terrestrial point-to-point applications of wireless power transmission (WPT).[5] For example, a specific power transmission challenge has been examined for a number of years in Canada involving transmission at the Straits of Belle Isle. The Straits present a difficult challenge for conventional power transmission because they are subject to the presence of strong tidal currents, sea ice and icebergs, and the underlying bedrock is Canadian Shield granite. With respect to wireless power transmission, the distance across varies from 60 km to as little as 15 km, with an average of 18 km. The area is, however, subject to severe weather conditions and frequent high winds.

Another Canadian power transmission challenge is that of providing power to remote settlements or to mining or other commercial operations at locations that are inaccessible from the primary power grid. In such cases, the power requirements can be substantial (ranging from 1 MW to 10s of MWs, and the distance over which power might be transmitted can range from 10s of km to a few 100s of km. (The maximum achievable distance using a line-of-sight system is limited by the curvature of the Earth's surface, obstacles in the path, etc.)

Recent studies sponsored by SPACE Canada (a non-profit based in Canada) have explored whether there may be early "niche" market opportunities for WPT in geographically isolated and environmentally sensitive locations. Figure 12-2 illustrates a concept examined in one of these recent studies.

Figure 12-2 Illustration from a Recent Study of Point-to-Point WPT



Transmitter

Receiver

Credit: SPACE Canada (2013)

The basic finding from these studies was that WPT can make economic sense for point-to-point power transfer if the existing services are expensive and restricted – for example, in circumstances where power must be locally generated using petroleum fuels that have been shipped in (by air or by truck). In some cases, the latter is only possible during the cold of winter when ice roads can be constructed. (During the spring and summer months, the warmth melts the ice and results in the ground routes becoming impassable.)

Because of the remoteness of the locations involved, the lowest-cost providers (utilities and the electrical grid) do not currently provide power to this class of applications, of course; rather, operations usually involve diesel-fueled power generators. As a result, in these prospective niche markets, the cost typically falls in the range of 50¢ per kilowatt-hour or more. Because weather interference and risks to local flora and fauna preclude laser power transmission, microwave power at low-to-moderate intensity may be an option. As a result, if they are to be viable, these applications must therefore involve relatively short distances (up to tens of kilometers) and relatively high power requirements (roughly 10 MW or so). Such markets typically involve industrial activities by a single corporation or which are motivated by some government policy. The activities of the former customer would tend to be of relatively short duration (i.e., 4-10 years), while the latter might often persist for some decades. This is a market that could be served as soon as the next 2-3 years, or any time afterward.

Market Opportunities Summary

There are a variety of prospective terrestrial markets for Space Solar Power, ranging from traditional baseload power markets in the US to broader global markets as well as to specialized energy markets. These markets exist today, and may be expected to continue in the future. However, as we previously discussed, making predictions is difficult, especially about the future! In Chapter 2, we developed a set of Strategic Scenarios, and high-level market forecasts that were intended to mitigate uncertainty by examining a range of divergent futures. Based on these scenarios, the tables on the following two pages (Table 12-2a and 12-2b) present some rather specific, quantitative forecasts for the specific market areas that we've discussed in the Chapter.

The tables present the "worst market" case and the "typical market" case for Space Solar Power – representing Scenario Zero and Scenario Gamma, respectively (i.e., "business as usual works out," and "aggressive energy innovation"). If either of the other two cases happens to occur – namely, Scenario Alpha (i.e., a climate disaster) or Scenario Beta (i.e., fossil fuels run out suddenly) – the situation is bracketed by the two cases summarized below.

Table 12-2a 100-Year Forecast of Wholesale Prices by Region – "Worst Market" Case[a]

		2010	2030-40	2060-70	2090-2100
Projected Total Annual Energy Consumption [6]		~ 120,000 Billion kWh	~220,000 Billion kWh	~ 400,000 Billion kWh	~ 480,000 Billion kWh
		Wholesale Price - Scenario Shown-	Wholesale Price -Scenario Shown-	Wholesale Price - Scenario Shown-	Wholesale Price - Scenario Shown-
Americas (North/South)	Commercial Market - Baseload Power	5¢-10¢ per kW-hr (Scenario **Zero)**	5¢-10¢ per kW-hr (Scenario **Zero)**	10¢-20¢ per kW-hr (Scenario **Zero**)	10¢-20¢ per kW-hr (Scenario **Zero**)
	Carbon-Reduction Incentive Power	10¢-15¢ per kW-hr (Scenario **Zero)**	10¢-15¢ per kW-hr (Scenario **Zero)**	15¢-20¢ per kW-hr (Scenario **Zero)**	15¢-20¢ per kW-hr (Scenario **Zero)**
	Niche, Intermediate & Peaking Power	20¢-40¢ per kW-hr (Scenario **Zero**)	20¢-40¢ per kW-hr (Scenario **Zero**)	30¢-60¢ per kW-hr (Scenario **Zero**)	30¢-60¢ per kW-hr (Scenario **Zero**)
	Security-Related Premium Niche Market Power	$2.00-$2.50 per kW-hr (Scenario **Zero)**	$2.00-$2.50 per kW-hr (Scenario **Zero)**	$3.00-$4.00 per kW-hr (Scenario **Zero)**	$3.00-$4.00 per kW-hr (Scenario **Zero)**
Asia-Pacific	Commercial Market - Baseload Power	10¢-15¢ per kW-hr (Scenario **Zero)**	10¢-15¢ per kW-hr (Scenario **Zero)**	15¢-22¢ per kW-hr (Scenario **Zero)**	15¢-22¢ per kW-hr (Scenario **Zero)**
	Carbon-Reduction Incentive Power	10¢-15¢ per kW-hr (Scenario **Zero)**	15¢-20¢ per kW-hr (Scenario **Zero)**	22¢-30¢ per kW-hr (Scenario **Zero)**	22¢-30¢ per kW-hr (Scenario **Zero)**
	Niche, Intermediate & Peaking Power	20¢-40¢ per kW-hr (Scenario **Zero)**	20¢-40¢ per kW-hr (Scenario **Zero)**	30¢-60¢ per kW-hr (Scenario **Zero**)	30¢-60¢ per kW-hr (Scenario **Zero**)
	Security-Related Premium Niche Market Power	$2.00-$2.50 per kW-hr (Scenario **Zero)**	$2.00-$2.50 per kW-hr (Scenario **Zero)**	$3.00-$4.00 per kW-hr (Scenario **Zero)**	$3.00-$4.00 per kW-hr (Scenario **Zero)**
Africa-Middle	Commercial Market - Baseload Power	10¢-20¢ per kW-hr (Scenario **Zero)**	10¢-20¢ per kW-hr (Scenario **Zero)**	15¢-30¢ per kW-hr (Scenario **Zero)**	15¢-30¢ per kW-hr (Scenario **Zero)**

		2010	2030-40	2060-70	2090-2100
Projected Total Annual Energy Consumption [6]		~ 120,000 Billion kWh	~220,000 Billion kWh	~ 400,000 Billion kWh	~ 480,000 Billion kWh
		WHOLESALE PRICE - Scenario Shown-	WHOLESALE PRICE -Scenario Shown-	WHOLESALE PRICE - Scenario Shown-	WHOLESALE PRICE - Scenario Shown-
	Carbon-Reduction Incentive Power	15¢-30¢ per kW-hr (Scenario **Zero)**	15¢-30¢ per kW-hr (Scenario **Zero)**	22¢-45¢ per kW-hr (Scenario **Zero)**	22¢-45¢ per kW-hr (Scenario **Zero)**
	Niche, Intermediate & Peaking Power	20¢-40¢ per kW-hr (Scenario **Zero)**	20¢-40¢ per kW-hr (Scenario **Zero)**	30¢-60¢ per kW-hr (Scenario **Zero**)	30¢-60¢ per kW-hr (Scenario **Zero**)
	Security-Related Premium Niche Market Power	$2.00-$2.50 per kW-hr (Scenario **Zero)**	$2.00-$2.50 per kW-hr (Scenario **Zero)**	$3.00-$4.00 per kW-hr (Scenario **Zero)**	$3.00-$4.00 per kW-hr (Scenario **Zero)**

[a] Note: the “worst case” for Space Solar Power is the current market, with modest changes through 2100

Table 12-2b 100-Year Forecast of Wholesale Prices by Region – “Nominal Market”[b]

		2010	2030-40	2060-70	2090-2100
Projected Total Annual Energy Consumption [7]		~ 120,000 Billion kWh	~220,000 Billion kWh	~ 400,000 Billion kWh	~ 480,000 Billion kWh
		WHOLESALE PRICE - Scenario Shown-	WHOLESALE PRICE -Scenario Shown-	WHOLESALE PRICE - Scenario Shown-	WHOLESALE PRICE - Scenario Shown-
AMERICAS (North/South)	Commercial Market - Baseload Power	5¢-10¢ per kW-hr (Scen. **Gamma)**	10¢-20¢ per kW-hr (Scen. **Gamma)**	10¢-20¢ per kW-hr (Scen. **Gamma)**	10¢-20¢ per kW-hr (Scen. **Gamma)**
	Carbon-Reduction Incentive Power	10¢-15¢ per kW-hr (Scen. **Gamma)**	10¢-20¢ per kW-hr (Scen. **Gamma)**	10¢-20¢ per kW-hr (Scen. **Gamma)**	10¢-20¢ per kW-hr (Scen. **Gamma)**
	Niche, Intermediate & Peaking Power	20¢-40¢ per kW-hr (Scen. **Gamma)**	35¢-30¢ per kW-hr (Scen. **Gamma)**	35¢-30¢ per kW-hr (Scen. **Gamma)**	35¢-30¢ per kW-hr (Scen. **Gamma)**
	Security-Related Premium Niche Market Power	$2.00-$2.50 per kW-hr (Scen. **Gamma)**	$2.00-$2.50 per kW-hr (Scen. **Gamma)**	$3.00-$4.00 per kW-hr (Scen. **Gamma)**	$3.00-$4.00 per kW-hr (Scen. **Gamma)**
ASIA-PACIFIC	Commercial Market - Baseload Power	10¢-15¢ per kW-hr (Scen. **Gamma)**	15¢-22¢ per kW-hr (Scen. **Gamma)**	15¢-22¢ per kW-hr (Scen. **Gamma)**	15¢-22¢ per kW-hr (Scen. **Gamma)**
	Carbon-Reduction Incentive Power	10¢-15¢ per kW-hr (Scen. **Gamma)**	15¢-20¢ per kW-hr (Scen. **Gamma**)	15¢-20¢ per kW-hr (Scen. **Gamma**)	15¢-20¢ per kW-hr (Scen. **Gamma**)
	Niche, Intermediate & Peaking Power	20¢-40¢ per kW-hr (Scen. **Gamma)**	30¢-60¢ per kW-hr (Scen. **Gamma)**	30¢-60¢ per kW-hr (Scen. **Gamma)**	30¢-60¢ per kW-hr (Scen. **Gamma)**
	Security-Related Premium Niche Market Power	$2.00-$2.50 per kW-hr (Scen. **Gamma)**	$2.00-$2.50 per kW-hr (Scen. **Gamma)**	$3.00-$4.00 per kW-hr (Scen. **Gamma)**	$3.00-$4.00 per kW-hr (Scen. **Gamma)**
EUROPE-AFRICA-MIDDLE EAST	Commercial Market - Baseload Power	10¢-20¢ per kW-hr (Scen, **Gamma)**	15¢-30¢ per kW-hr (Scen. **Gamma)**	15¢-30¢ per kW-hr (Scen. **Gamma)**	20¢-40¢ per kW-hr (Scen. **Gamma)**
	Carbon-Reduction Incentive Power	15¢-30¢ per kW-hr	22¢-45¢ per kW-hr	22¢-45¢ per kW-hr	30¢-60¢ per kW-hr

	2010	2030-40	2060-70	2090-2100
Projected Total Annual Energy Consumption [7]	~ 120,000 Billion kWh	~220,000 Billion kWh	~ 400,000 Billion kWh	~ 480,000 Billion kWh
	WHOLESALE PRICE - Scenario Shown-	WHOLESALE PRICE -Scenario Shown-	WHOLESALE PRICE - Scenario Shown-	WHOLESALE PRICE - Scenario Shown-
	(Scen. **Gamma)**	(Scen. **Gamma)**	(Scen. **Gamma)**	(Scen. **Gamma)**
Niche, Intermediate & Peaking Power	20¢-40¢ per kW-hr (Scen. **Gamma)**	30¢-60¢ per kW-hr (Scen. **Gamma)**	30¢-60¢ per kW-hr (Scen. **Gamma**	40¢-80¢ per kW-hr (Scen. **Gamma**
Security-Related Premium Niche Market Power	$2.00-$2.50 per kW-hr (Scen. **Gamma)**	$2.00-$2.50 per kW-hr (Scen. **Gamma)**	$3.00-$4.00 per kW-hr (Scen. **Gamma)**	$3.00-$4.00 per kW-hr (Scen. **Gamma)**

[b] Note: the “nominal case” for Space Solar Power is the market with aggressive energy innovation.

Concluding Observations

There seem to me to be four "types" of people in the OECD countries with respect to questions of energy, climate, and economic opportunity for the world's population. The first – and by far the largest – group is that of people who really don't even think about the question at all. These individuals flip a switch and the lights come on. The only time many people think about energy is when there is a rare blackout, or if the price of gasoline spikes.

The second group comprises those who recognize the issue, but are confident that existing fuels (oil, coal, natural gas) will remain the dominant sources of power indefinitely – i.e., for the remainder of this century and more. These individuals may or may not accept the limits of hydrocarbon fuels as a theoretical fact, but they do not regard such limits as being of any practical importance. The third type is composed of those people who believe that we must make the transition to sustainable energy sources (either because of climate concerns or limits on hydrocarbons, or both). However, these individuals also argue that the transition away from hydrocarbon-based energy can be made entirely with existing technologies, including wind, solar, biomass (and sometimes nuclear) power.

The final group – to which I confess being a member – comprises those believing as do the third group that we cannot change overnight, but that we must make the transition away from reliance on hydrocarbon fuels. However, this fourth group also believes that existing sustainable energy solutions are not going to be able to meet the rapidly growing demand for affordable power when and where needed while also drastically reducing greenhouse gas emissions. To this fourth group, the need during the coming decades to achieve massive increases in global and sustainable energy supplies is clear and compelling. As we discussed in Chapter 2, the scientific community's consensus concerning the risks of greenhouse gas emissions combined with the inevitable decline in fossil fuel production drives strong interest and economic incentives to develop sustainable new energy supplies.

Beginning there, the discussion above examined in some detail how these global longer-term concerns translate into the tactical terrestrial energy market for Space Solar Power. The several strategic Scenarios defined in Chapter 2 represent a range of potential markets into which Space Solar Power might enter the market during the coming several decades. Of the Scenarios examined, the "worst" market as such for SSP is that in which "business as usual" turns out to be good enough (i.e., if Scenario Zero is correct). Conversely, the "best" market is the one in which fossil fuels run out early and unexpectedly (i.e., Scenario Beta).

As we saw, even in present markets, there are significant opportunities for Space Solar Power – if the levelized cost of electricity (LCOE) is competitive. These opportunities are global in character; they are great in premium markets (for example, islands or some otherwise isolated location) and they will continue during the remainder of this century. The SPS-ALPHA concept has the potential to meet this goal as soon as the next 15-20 years, although the first versions of the platform – the early DRMs when production is ramping up – will be far more expensive.

With this background then – a broad range of space mission applications beginning in the immediate future, and strong and continuing terrestrial demand for new sustainable energy – an integrated economic case for Space Solar Power may be attempted. This is the goal of the Chapter that follows.

[12-1] See: Li, Junfeng, et al, "Energy and Environment in China," (China Renewable Energy Industry Association, Renewable Energy And Energy Efficiency Partnership). May 2011.

[12-2] "Syngas" is a mixture of Hydrogen, Carbon Monoxide, and other gases; it is typically produced by heating a feedstock such as coal or natural gas in the presence of superheated steam.

[12-3] There were a great many references for this table; for example, for the US data, see: http://www.eia.gov/. For the highest prices in California, I used my personal electric bill.The data for the Bahamas comprises some 10¢-13¢ per kW-hr in power generation cost, and a fuel consumption surcharge of roughly 25¢ per kW-hr.

[12-4] For useful information on this topic, see: http://world-nuclear.org/info/Economic-Aspects/Energy-Subsidies-and-External-Costs/#.UbTaO4VUiOg

[12-5] Kieran A. Carroll (founding Director and Past-President of the Canadian Space Society, and currently Chief Technology Officer at Gedex Inc.) presented a thorough review of these past efforts at the SPS 2009 International Symposium and Workshop in Toronto, Canada in September 2009.

[12-6] This overall projection was explained in Chapter 2.

[12-7] This overall projection was explained in Chapter 2.

Chapter 13

The Integrated Business Case

> *"The concept is interesting and well-formed, but in order to earn better than a 'C,' the idea must be feasible."*
>
> *A Yale University Management Professor (1966)*
> *in response to a paper by student Fred Smith (later founder of Federal Express) proposing overnight package delivery1*

Overview

Space Solar Power (SSP) – regardless of how elegant an idea it might be – will never be pursued unless it can be shown to make economic sense. In Chapter 10, we examined a series of Design Reference Missions (DRMs) that when taken together represent a series of doable steps toward the realization of a hyper-modular approach to SSP. In the two chapters that followed (11 and 12), we identified and characterized a number of distinct markets for SPS-ALPHA. This Chapter integrates the DRMs and the market opportunities in financial terms, synthesizing the pieces into a business case for Space Solar Power in general and for SPS-ALPHA in particular. Let's begin with a recap of the principal building blocks for SPS-ALPHA: the Design Reference Missions.

SPS-ALPHA Design Reference Missions

The programmatic strategy for SPS-ALPHA comprises several key steps that represent both technology milestones and staged increases in manufacturing capacity. Table 13-1 presents the selected specifications for the DRMs, which are cornerstones of the business case for Space Solar Power. They are: DRM-1 (a first flight demonstration); DRM-2 (the first technology flight demonstration in LEO integrating all of the operational capabilities that will be needed for GEO); DRM-3 (an SPS pilot plant); DRM-4 (the first full-scale SPS); and, DRM-5 (a recurring full-scale SPS for commercial markets with advanced technology). DRM-0, an initial ground technology testbed, is not shown in the table; however, details of this case may be found in Chapter 10.

Table 13-1 SPS-ALPHA Design Reference Missions Summary

Parameters	**DRM-1** (SPS-ALPHA First Demo, with Minimal Tech Advances)	**DRM-2** (SPS-ALPHA Integrated Demo, with Minimal Adv. Technology)	**DRM-3** (SPS-ALPHA Pilot Plant, with Minimal Adv. Technology)	**DRM-4** (First Full-size SPS, with Selected Technology Enhancements)	**DRM-5** (Recurring SPS, with Continuing Technology Improvements)
Power Delivered to Earth	N/A (Power on Board @ 30 kW)	N/A (Power on Board @ 200 kW)	18 MW	500 MW	2,000 MW
WPT Transmission Frequency	2.45 GHz	2.45 GHz	2.45 GHz	2.45 GHz	2.45 GHz
Solar Power Gen. Efficiency	25% BOL	25% BOL	25% BOL	48% BOL	60% BOL
WPT Efficiency (Percentage)	70% (DC-to-RF)	70% (DC-to-RF)	70% (DC-to-RF)	70% (DC-to-RF)	80% (DC-to-RF)
ETO Cost ($/kg)	$4,000/kg	$4,000/kg	$1,500/kg	70% (DC-to-RF)	> 70% (DC-to-RF)
Cost to "First Power" (estimated at Earth)	~$ 50-100 M	~$ 100 M	~$ 4.5 B (~$250 / Watt)	~$ 12.2 B (~$24 / Watt)	~$ 31 B (~$16 / Watt)
Lifetime	1 years	1-2 years	10-15 years	> 30 yrs (with Spares & Maintenance)	> > 30 years (with Spares & Maintenance)
Levelized Cost of Electricity (LCOE; $/kW-hr)	N/A	N/A	~ $3.26 per kW-hr	~ 15¢ per kW-hr	~ 9¢ per kW-hr

You may recall that DRM-3, DRM-4 and DRM-5 are GEO-based platforms (at 35,800 km altitude), where DRM-1 and DRM-2 (and DRM-0, not shown) would be located in LEO. For DRM-4 and DRM-5, each of the cases described assumes a lifetime per module of approximately 20-30 years, and a time between refueling of 5 years. The period of economic interest of the full-scale SPS platform described as DRM-5 (including regular maintenance and repair) is of indefinite duration; however, the period for determination of the LCOE (levelized cost of electricity) is limited to 30 years, consistent with electric power industry practices. In addition, for purposes of this discussion, during the initial deployment of DRM-4 and DRM-5, transportation costs have been estimated at \$400-\$500 per kg for Earth-to-orbit (ETO) transport and \$300-\$400 per kg for LEO to GEO transport.

In the above discussion, selected improvements in technology were assumed for DRM-5 (e.g., WPT efficiency and PV efficiency). As we saw in Chapter 10, some combination of advances necessary to reach the baseload power LCOE goal of less than 9¢ per kWh. It need not be the specific set of advances assumed here, however. We'll discuss the technologies needed for DRM-5 to achieve financial feasibility further in the next Chapter.

In addition to the five Design Reference Missions that emerged from the NASA-sponsored study in 2011-2012, a sixth DRM was defined for purposes of the economic analysis presented here: "DRM-0." It reflects an initial ground testbed which might later be flown as an early experiment in LEO; it comprises only ten or twelve Hexbus units and associated other modules. The costs for this first test article are included in the initial two years of the integrated economic results presented below.

SPS-ALPHA Markets

Space Mission Applications and Market Opportunities

The space business sector has grown over the past two decades to some tens of billions of dollars per year, with government programs now representing only a minority share of the total. Services from space – communications, position and navigation (i.e., GPS), direct broadcast (television and audio) – and the infrastructures that enable these (i.e., launch services) have become the mainstay of the space sector. As discussed in Chapter 11, both government and private sector space markets present tremendous opportunities for SPS-ALPHA technologies and systems – beginning as soon as new systems become available. Table 13-2 summarizes these opportunities.

For the most part, the potential revenues shown in Table 13-2 are notional (at best). These wholesale price projections are based on the known costs for similar systems or services as they are, or would be, provided by existing architectures or systems. For example, the overall satellite industry in 2012 had a value of just less than $190 billion, within which satellite manufacturing represented somewhat less than $15 billion.[2] With existing architectures, a 20 kW GEO communications satellite (commsat) would likely cost about $100M-$200M or more.[3] By extension, the first large aperture 200 kW commsat in GEO using a conventional architecture would likely cost more than $1B, and perhaps as much as $2B-$3B. The projected SPS-ALPHA revenue opportunity shown in Table 13-2 is $500M with the expectation that this is a wholesale price that would be acceptable to a customer who would otherwise have paid 2-to-6 times more.

Let's walk through a civil mission example: power for exploration outposts on the Moon or Mars. During the past 25 years, power for such an outpost has usually been assumed to be provided by a small space nuclear reactor (SNR), where different versions with unique materials and design would be needed on the Moon or on Mars (due to the differences between the environments in the two locations). Estimating the cost of such a system is difficult; however, we may use the same rules-of-thumb that we discussed before. For a power level of about 100 kW, an SNR (of the Prometheus type) might have a mass of about 5-10 MT, including the large radiators required,[4] and the development cost may be expected to be in excess of some $2-$3 billion.[5] That works out to about $20M-$30M per kilowatt, or (over a ten-year lifetime) about $230 to $340 per kilowatt-hour, a value that that does not include the costs of transportation or operations. (If the cost of deploying an SNR on the surface of the Moon or Mars is high, which seems likely, then the advantage grows – as would the opportunity for SPS-ALPHA revenues.) Given that the surface infrastructure required would be exorbitantly expensive, the projected revenue opportunity for SPS-ALPHA is shown in Table 13-2 as $20-$40 per kWh for power delivered to the Lunar or Mars surface (up to 1 MW) – or about 10% of the cost of the expected alternative technical solution. The other items in the table were estimated similarly.

Obviously, where a government policy goal (such as a Human Mars Mission) requires future development of systems and implementation of a mission, preliminary R&D would typically precede the program itself. Such potential R&D revenues are discussed below.

All told, there are a wide variety of space mission applications, some of which we discussed in Chapter 11 that would represent prospective future customers for SPS-ALPHA. These opportunities include both government applications as well as a range of commercial markets.

Table 13-2 Summary of SPS-ALPHA Space Application Markets

MARKET TYPE / SEGMENT	MARKET OPPORTUNITY	LOCATION(S)	TIME FRAME*	POTENTIAL REVENUES
Applications & Markets in Earth Orbit	Comm. Satellite Constellation	Low Earth Orbit	Nearer-Term > 5 years	$500M per each 5 Years
	Broadband Comm. Satellites	Geostationary Earth Orbit	Nearer-Term > 5-10 years	$500M per Year
	Position, Location & Navigation	Middle Earth Orbit	Nearer-Term > 5-10 years	$500M per each 5-10 Years
	Earth Observing Satellites	Geostationary Earth Orbit	Nearer-Term > 5-10 years	$500M per each 2-3 Years
	Orbit-to-Orbit Space Transport	Various Orbits…	Nearer-Term > 10 years	$100M-$200M per Year
	Servicing or Debris Mitigation	Various Orbits	Nearer-Term > 10 years	$100M-$200M per Year
Earth's Vicinity and the Moon	Deep Space Optical Comm	Earth-Moon Libration Point	Mid-Term > 5-10 years	$500M per 5-10 Years
	Lunar Surface Point-to-Point	Lunar Surface	Mid-Term > 15-20 years	$500M per 10 Years
	Power to the Lunar Surface	Lunar Orbit	Mid-Term > 15-20 years	Up to 1 MW @ $20-$40 per kW-hr
Applications & Markets Beyond the Earth's Vicinity and the Moon	Deep Space Solar Sails	Outer Planets	Mid-Term > 15 years	$100M-$200M per each 5-10 Years
	Human Mission Transport to Small Bodies / Mars	Earth Orbit to Near-Earth Space & Mars Orbit	Mid-Term > 15 years	$1B-$2B per each 3-5 Years
	SPS WPT Power to the Mars Surface	Mars Orbit	Mid-Term > 20 years	Up to 1 MW @ $20-$40 per kW-hr
	Extremely Large Telescopes (TPI)	Sun-Earth Libration Points	Farther-Term > 20 years	$1B-$2B per each 6-12 Years

*Note: Timeframe shown is first opportunity; continuing for later timeframes.

Energy Markets on Earth

As we've discussed, there is a tremendous global demand for new sources of energy and, particularly, for sustainable energy at an affordable price. Fortunately, this demand is not limited to the important goal of electrical power delivered at a cost of less than 10¢ per kilowatt-hour. (If this had been the case, no new energy technologies would have been introduced during the past thirty-plus years.) Rather, the market includes demand for power at considerably higher prices based on geographic isolation, policy-driven incentives, or security related issues.

Allowing for Uncertainty. Although in the nearer-term (i.e., during the next 10-20 years), the global energy market is likely to be much like that at present, there is considerable uncertainty after that (beyond 20 years). In Chapter 2 we developed an approach to allow for that uncertainty: the use of Strategic Scenarios. And at the end of Chapter 12, two alternative market futures were detailed: a baseline case (derived from Scenario Zero, "business as usual") and an enhanced revenue case (derived from Scenario Gamma, "sustainable energy early"). Now, we must make the Scenarios more "concrete" so that the consequences of each alternative for SPS-ALPHA can be described and compared. Table 13-2 provides a summary of terrestrial energy opportunities; Table 13-2a for the baseline case (only modest changes from today), and 13-2b for Scenario Gamma.[6]

How much energy is represented in the two parts of Table 13-2, and is it reasonable to suppose that Space Solar Power could deliver this much? Of course, today's energy mix includes substantial fractions for transportation and heating, not just electricity; however, it is impossible to project what the mix will be in 100 years. Still, the projected market opportunities for SSP in Table 13-2 are intended to be conservative – i.e., readily achievable – within the scope of the overall market.

As shown in Table 13-2a (based on Scenario Zero), the total annual energy represented by the farthest-term column (i.e., 2090-2100) is about 6,700 Billion kilowatt-hours from a total capacity of more than 770 GW (depending on the availability). Similarly, in Table 13-2b (based on Scenario Gamma), the total annual energy in the far term is approximately 18,800 Billion kilowatt-hours from a total capacity of more than 2100 GW (again, depending on availability).

The two values represent only approximately 1.4% and 3.9%, respectively, of the total demand for energy by the end of the century.

Table 13-3a Integrated SPS-ALPHA Terrestrial Energy Market – “Baseline” Case[a]

		2010	2030-40	2060-70	2090-2100
Projected Total Annual Energy Consumption [7]		~ 120,000 Billion kWh	~220,000 Billion kWh	~ 400,000 Billion kWh	~ 480,000 Billion kWh
		Available Market & Wholesale Price	Available Market & Wholesale Price	Available Market & Wholesale Price	Available Market & Wholesale Price
Commercial Market - Baseload Power	Americas (North / South)	Up to 20 GW @ 5¢-10¢ per kW-hr	Up to 40 GW @ 5¢-10¢ per kW-hr	Up to 80 GW @ 10¢-20¢ per kW-hr	Up to 160 GW @ 10¢-20¢ per kW-hr
	Asia-Pacific	Up to 20 GW @ 10¢-15¢ per kW-hr	Up to 40 GW @ 10¢-15¢ per kW-hr	U Up to 80 GW @ 15¢-22¢ per kW-hr	Up to 160 GW @ 15¢-22¢ per kW-hr
	Europe-Africa-Middle East	Up to 20 GW @ 10¢-20¢ per kW-hr	Up to 40 GW @ 10¢-20¢ per kW-hr	Up to 80 GW @ 15¢-30¢ per kW-hr	Up to 160 GW @ 15¢-30¢ per kW-hr
Carbon-Reduction Incentive Power	Americas (North / South)	Up to 10 GW @ 10¢-15¢ per kW-hr	Up to 20 GW @ 10¢-15¢ per kW-hr	Up to 40 GW @ 15¢-20¢ per kW-hr	Up to 80 GW @ 15¢-20¢ per kW-hr
	Asia-Pacific	Up to 10 GW @ 10¢-15¢ per kW-hr	Up to 20 GW @ 15¢-20¢ per kW-hr	Up to 40 GW @ 22¢-30¢ per kW-hr	Up to 80 GW @ 22¢-30¢ per kW-hr
	Europe-Africa-Middle East	Up to 10 GW @ 15¢-30¢ per kW-hr	Up to 20 GW @ 15¢-30¢ per kW-hr	Up to 40 GW @ 22¢-45¢ per kW-hr	Up to 80 GW @ 22¢-45¢ per kW-hr
Niche, Intermediate & Peaking Power	Americas (North / South)	Up to 2 GW @ 20¢-40¢ per kW-hr	Up to 4 GW @ 20¢-40¢ per kW-hr	Up to 8 GW @ 30¢-60¢ per kW-hr	Up to 16 GW @ 30¢-60¢ per kW-hr
	Asia-Pacific	Up to 2 GW @ 20¢-40¢ per kW-hr	Up to 4 GW @ 20¢-40¢ per kW-hr	Up to 8 GW @ 30¢-60¢ per kW-hr	Up to 16 GW @ 30¢-60¢ per kW-hr
	Europe-Africa-Middle East	Up to 2 GW @ 20¢-40¢ per kW-hr	Up to 4 GW @ 20¢-40¢ per kW-hr	Up to 8 GW @ 30¢-60¢ per kW-hr	Up to 16 GW @ 30¢-60¢ per kW-hr
Security-Related Premium Niche Market Power[b]	Americas (North / South)	Up to 5*10 MW @ $2.00-$2.50 per kW-hr	Up to 5*10 MW @ $2.00-$2.50 per kW-hr	Up to 5*10 MW @ $3.00-$4.00 per kW-hr	Up to 5*10 MW @ $3.00-$4.00 per kW-hr
	Asia-Pacific	Up to 5*10 MW @ $2.00-$2.50 per kW-hr	Up to 5*10 MW @ $2.00-$2.50 per kW-hr	Up to 5*10 MW @ $3.00-$4.00 per kW-hr	Up to 5*10 MW @ $3.00-$4.00 per kW-hr

		2010	2030-40	2060-70	2090-2100
Projected Total Annual Energy Consumption [7]		~ 120,000 Billion kWh	~220,000 Billion kWh	~ 400,000 Billion kWh	~ 480,000 Billion kWh
		Available Market & Wholesale Price	Available Market & Wholesale Price	Available Market & Wholesale Price	Available Market & Wholesale Price
	Europe-Africa-Middle East	Up to 5*10 MW @ $2.00-$2.50 per kW-hr	Up to 5*10 MW @ $2.00-$2.50 per kW-hr	Up to 5*10 MW @ $3.00-$4.00 per kW-hr	Up to 5*10 MW @ $3.00-$4.00 per kW-hr

[a] Note: the "baseine" case for Space Solar Power is the current market, with modest changes through 2100

[b] Note: for the security related values in the table, "Up to 5*10 MW"…" indicates that there may be up to 5 locations, each needing as much as 10 MW of power.

Table 13-3b Integrated SPS-ALPHA Terrestrial Energy Market – "Enhanced" Case[a]

		2010	2030-40	2060-70	2090-2100
Projected Total Annual Energy Consumption [8]		~ 120,000 Billion kWh	~220,000 Billion kWh	~ 400,000 Billion kWh	~ 480,000 Billion kWh
		AVAILABLE MARKET & WHOLESALE PRICE	AVAILABLE MARKET & WHOLESALE PRICE	AVAILABLE MARKET & WHOLESALE PRICE	AVAILABLE MARKET & WHOLESALE PRICE
Commercial Market - Baseload Power	AMERICAS (NORTH / SOUTH)	Up to 20 GW @ 5¢-10¢ per kW-hr	Up to 40 GW @ 10¢-20¢ per kW-hr	Up to 80 GW @ 10¢-20¢ per kW-hr	Up to 160 GW @ 10¢-20¢ per kW-hr
	ASIA-PACIFIC	Up to 20 GW @ 10¢-15¢ per kW-hr	Up to 40 GW @ 10¢-15¢ per kW-hr	U Up to 80 GW @ 15¢-22¢ per kW-hr	Up to 160 GW @ 15¢-22¢ per kW-hr
	EUROPE-AFRICA-MIDDLE EAST	Up to 20 GW @ 10¢-20¢ per kW-hr	Up to 40 GW @ 10¢-20¢ per kW-hr	Up to 80 GW @ 15¢-30¢ per kW-hr	Up to 160 GW @ 15¢-30¢ per kW-hr
Carbon-Reduction Incentive Power	AMERICAS (NORTH / SOUTH)	Up to 20 GW @ 10¢-15¢ per kW-hr	Up to 60 GW @ 10¢-20¢ per kW-hr	Up to 180 GW @ 10¢-20¢ per kW-hr	Up to 540 GW @ 10¢-20¢ per kW-hr
	ASIA-PACIFIC	Up to 20 GW @ 10¢-15¢ per kW-hr	Up to 60 GW @ 15¢-20¢ per kW-hr	Up to 180 GW @ 15¢-20¢ per kW-hr	Up to 540 GW @ 15¢-20¢ per kW-hr
	EUROPE-AFRICA-MIDDLE EAST	Up to 20 GW @ 15¢-30¢ per kW-hr	Up to 60 GW @ 22¢-45¢ per kW-hr	Up to 160 GW @ 22¢-45¢ per kW-hr	Up to 540 GW @ 30¢-60¢ per kW-hr
Niche, Intermediate & Peaking Power	AMERICAS (NORTH / SOUTH)	Up to 2 GW @ 20¢-40¢ per kW-hr	Up to 4 GW @ 35¢-30¢ per kW-hr	Up to 8 GW @ 35¢-30¢ per kW-hr	Up to 16 GW @ 35¢-30¢ per kW-hr
	ASIA-PACIFIC	Up to 2 GW @ 20¢-40¢ per kW-hr	Up to 4 GW @ 20¢-40¢ per kW-hr	Up to 8 GW @ 30¢-60¢ per kW-hr	Up to 16 GW @ 30¢-60¢ per kW-hr
	EUROPE-AFRICA-MIDDLE EAST	Up to 2 GW @ 20¢-40¢ per kW-hr	Up to 4 GW @ 30¢-60¢ per kW-hr	Up to 8 GW @ 30¢-60¢ per kW-hr	Up to 16 GW @ 40¢-80¢ per kW-hr
Security-Related Premium Niche Market Power	AMERICAS (NORTH / SOUTH)	Up to 5*10 MW @ $2.00-$2.50 per kW-hr	Up to 5*10 MW @ $2.00-$2.50 per kW-hr	Up to 5*10 MW @ $3.00-$4.00 per kW-hr	Up to 5*10 MW @ $3.00-$4.00 per kW-hr
	ASIA-PACIFIC	Up to 5*10 MW @ $2.00-$2.50	Up to 5*10 MW @ $2.00-$2.50	Up to 5*10 MW @ $3.00-$4.00	Up to 5*10 MW @ $3.00-

		2010	2030-40	2060-70	2090-2100
Projected Total Annual Energy Consumption [8]		~ 120,000 Billion kWh	~220,000 Billion kWh	~ 400,000 Billion kWh	~ 480,000 Billion kWh
		AVAILABLE MARKET & WHOLESALE PRICE	AVAILABLE MARKET & WHOLESALE PRICE	AVAILABLE MARKET & WHOLESALE PRICE	AVAILABLE MARKET & WHOLESALE PRICE
		per kW-hr	per kW-hr	per kW-hr	$4.00 per kW-hr
	EUROPE-AFRICA-MIDDLE EAST	Up to 5*10 MW @ $2.00-$2.50 per kW-hr	Up to 5*10 MW @ $2.00-$2.50 per kW-hr	Up to 5*10 MW @ $3.00-$4.00 per kW-hr	Up to 5*10 MW @ $3.00-$4.00 per kW-hr

[a] Note: the “enhanced” case for Space Solar Power is the market of Scenario Gamma; through 2100

Other Market Opportunities

In addition to space mission applications and terrestrial markets for sales of space power, there are also related prospects for revenues – particularly in the near-to-mid term – from various regional and national government programs. The latter might take several different forms, including direct funding for R&D programs that have been judged to be in the public interest and purchases of early new types of energy systems. Table 13-4 summarizes for the baseline case for these related government R&D and systems market opportunities.

Table 13-4 Summary of SPS-ALPHA – Government R&D and Systems

MARKET TYPE / SEGMENT	MARKET OPPORTUNITY	LOCATION(S)	TIME FRAME*	POTENTIAL REVENUES
SECONDARY MARKETS (Government R&D and Systems)	Adv. Concepts & Technology Research	Major Space Agencies (Civilian & Other)	Nearer-Term < 5 years	$100K-$2M (up to 1-3 Years)
	Technology Development Programs	Major Space Agencies (Civilian & Other)	Nearer-Term < 5 years	$1M-$5M (up to 3-5 Years)
	Technology Demonstration Programs	Major Space Agencies (Civilian & Other)	Nearer-Term < 5-10 years	$5M-$20M (up to 3-5 Years)
	System Demonstration Projects	Major Agencies (Civilian & Other)	Nearer-Term < 5-10 years	$20M-$1B per Project
	Fielding Operational Systems	Major Agencies (Civilian & Other)	Nearer-Term < 5-10 years	$100M-$1B Per Project

*Note: Timeframe shown is first opportunity; continuing for later timeframes.

In the Scenario Gamma case (involving the accelerated development of sustainable energy options), a range of technology and systems development programs would likely be implemented. However, it is difficult (if not impossible) to quantify how such new programs might impact funding for Space Solar Power R&D. As a result, the economic analysis presented in the section that follows involves only the baseline, which is based on programs and projects that have been implemented over the past decade.

Integrated Economic Analysis Results

As described earlier, the integrated economic case for SSP comprises (1) early funding from government R&D and systems development programs, (2) space mission applications and markets, and (3) terrestrial energy markets. The defined SPS-ALPHA Design Reference Missions (DRMs) would be address one or more of these markets over time. Table 13-5 summarizes a potential sequence of market events built around the DRMs that feed into several identified market opportunities.

These opportunities fall into four broad timeframes: (1) early markets (during the first six years; before DRM-3, the SPS-ALPHA Pilot Plant); (2) during the first ten years, up to the deployment of DRM-3; (3) initial full-scale Solar Power Satellites (DRM-4 and the first several DRM-5 platforms), out to approximately 30 years in the future; and (4) in the far term, mature SPS deployment and operations through the first 100 years following the beginning of Solar Power Satellite programs (including ongoing enhancements of technologies used in the initial versions of DRM-5). The paragraphs that follow summarize each of these four timeframes.

Early Markets

The early markets for SPS-ALPHA – beyond government-sponsorship for needed R&D and technology demonstrations (ground and space) – would comprise primarily space mission applications with the possibility of some point-to-point power transmission applications in niche markets around the world. The ability not just to consider but also to actually target these early markets is a critical feature of the new programmatic approach to SSP, enabled by the hyper-modular architecture. *Early space application markets and missions change the fundamental economic argument for Space Solar Power.* Let’s look at the details.

Figure 13-2 presents the integrated economic results in terms of the net finances (cost versus income) for the first six years, comprising early R&D (including initial test articles, such as the “DRM-0” that was mentioned previously), development and launch of DRM-1, most of the development of DRM-2, and the beginnings of investment in DRM-3.

The bottom line is quite appealing: a total investment over six years of $517M, results in revenues over the period of $1,392M, and a net income of $875B. Throughout the first six years – and all later years – there is assumed to be ongoing technology development at a level of a few million dollars per year, targeting key components for the SPS-ALPHA architecture. Note that during the nearer-term, no ancillary sales for space applications are shown of the DRM-2 version of the SPS-ALPHA platform, which only occurs in 2020. Nevertheless, the potential exists for significant financial returns during the first half-dozen years of a major effort to develop SSP; this is a really remarkable result. What are the details?

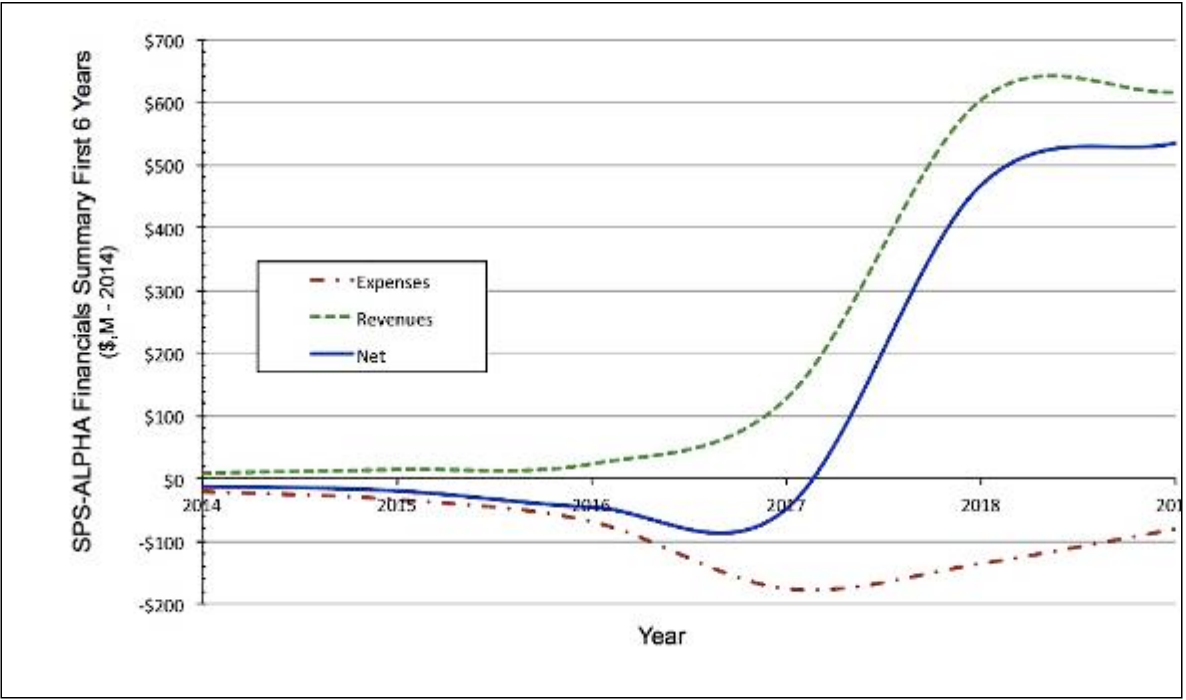
Table 13-3 Potential Sequence of Events and Markets for SPS-ALPHA

TIMEFRAME	MAJOR MILESTONE	MARKET OPPORTUNITIES
T = 0 years (e.g., 2013)	Research and Development	Contracted R&D for US / International Government Agencies
T = 2 ± 1 years (e.g., 2014-16)	Initial Ground Technology Demonstrations Small-Scale "DRM-0"	All of the above Niche Market Ground Applications (pt-to-pt) LEO / GEO Communications Satellite Applications (single launch)
T = 5 ± 2 years (e.g., 2016-2020)	DRM-1 (First LEO Technology Flight Experiment @ ~30kW on Board)	All of the above LEO / GEO Communications Satellite Applications (single launch)
T = 7 ± 2 years (e.g., 2018-2022)	DRM-2 (Initial Integrated Technology Flight Demonstration in LEO @ ~200kW on Board)	All of the above Large Commsats (MEO / GEO) Earth-Observing Platforms (MEO / GEO) Space-based Optical Deep Space Network Satellites Robust Satellite Servicing (LEO, GEO, etc.)
T = 11 ± 2 years (e.g., 2022-2026)	DRM-3 (Initial Solar Power Satellite (SPS) Pilot Plant in GEO @ ~18MW delivered to Earth)	All of the above Exploration & Development Transportation (NEOs, Moon, Mars, beyond) Multi-MW Exploration & Development Power throughout in the inner Solar System (in-space, Lunar and NEO surfaces) Premium Niche Market viable power @ less than ~$3.00 per kilowatt-hour
T = 14 ± 2 years (e.g., 2025-2029)	DRM-4 (First full-scale SPS in GEO @ 500MW delivered)	All of the above Space Access below $1,000 for Exploration & Development Carbon-incentive viable baseload power @ less than 9¢ per kilowatt-hour
T = 17 ± 2 years (e.g., 2028-2032)	DRM-5 (Initial Large-Scale SPS in GEO @ 2GW delivered)	All of the above Large-scale commercial baseload power @ an LCOE of about 10¢ per kilowatt-hour
T > 20 years (e.g., beyond 2032)	Ongoing Enhanced DRM-5 (Large-Scale GEO SPS @ 2GW delivered, with enhanced technology components)	All of the above Global commercial baseload power @ an LCOE less than 10¢ per kilowatt-hour The wholesale price for electricity (and hence economic performance) depends on the

		Scenario (“worst” versus “nominal”)

First, the financial analysis assumes (as shown in Table 13-3) that there will be low level programmatic support for SSP related R&D from various government programs; for example, from the Small Business Innovation Research (SBIR) program in the US. Second, these projections assume that there will be opportunities for joint government-industry cost-share programs to develop both DRM-1 and DRM-2.

Figure 13-2 Annual Financial Results for the First 6 Years (DRM-1 and -2)



Credit: Artemis Innovation Management Solutions LLC (2013)

As already discussed, governments have often used such programs to support new technologies of general public interest. These are relatively minor revenue opportunities, however. The key market for an SSP program based on a hyper-modular architecture during the early years comes from the opportunity to employ the various system elements (including the Hexbus Smallsats, HexFrame structures, etc.) to create radically lower cost and higher power commercial and government Earth-orbit satellites.

The downturn in the annual financial performance at around year six (in 2020) as shown in the figure is due in part to the increase in expenditures related to preparation for the deployment of DRM-3 (the Pilot Plant) and also to the reduction in revenues due to space mission applications sales. The latter is entirely the result of a not unreasonable, but perhaps somewhat conservative, projection that during the early years there will be a market for one LEO constellation, one commercial GEO satellite, and one government mission spacecraft.

All-in-all, the projected early markets for government and commercial Earth-orbiting spacecraft based on the SPS-ALPHA architecture are excellent, and promise a significant rate of return – if the low costs expected from the mass production of modular space systems can be realized.

Financials for the First Dozen Years

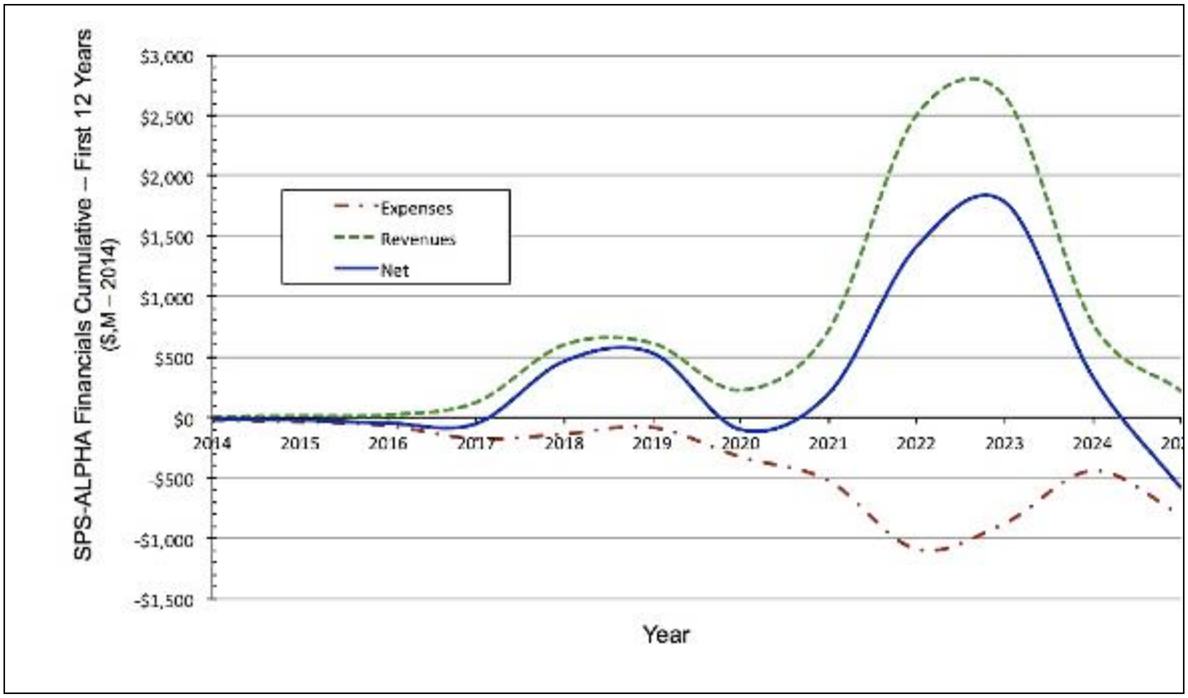
What comes next? As projected, the first twelve years of SSP development would comprise all of the components discussed above, including early R&D and initial technology flight demonstrations. To these would be added (1) deployment of DRM-2 and the beginning of sales of the demonstrated capabilities for SPS-ALPHA DRM-2, including higher power levels, robotic assembly, etc.; (2) the development and deployment of the first operational Solar Power Satellite in GEO: the SPS-ALPHA DRM-3 Pilot Plant; and (3) very early investments in the first large-scale SPS in GEO, DRM-4. See Figure 13-3 for a summary of the cumulative financial results for this period. Notice that the figure illustrates *cumulative* results through 2013 (ten years after the beginning of the projection); in other words, each year comprises the financial data for that year and for all years up to that point.

What about the bottom line for the first twelve years? It continues to be quite appealing (even with the beginning of DRM-4 manufacturing in the final year): a total investment of $4.6B over 12 years, resulting in revenues over the period of $8.5B, and a net income of just less than $4B.

Through the first dozen years of the proposed SPS-ALPHA business case – including the completion of DRM-3 (the Pilot Plant in GEO) and the beginning of sales of power to niche markets – the financial numbers look very promising. Several notes must be made, however. First, they do assume that there would be ongoing sales of space systems based on the capabilities developed for SPS-ALPHA – including, in particular, the addition of newer, much larger, and more capable systems in GEO.

However, these projections include no sales of terrestrial power from the small-scale SPS platform. Also, there is an explicit assumption that there will be government-industry cost sharing for the development of the Pilot Plant on the order of a 50%-50% split between participating governments and the commercial developer. (As we discussed previously, these types of arrangements are not new; in the US, they were used in the 1950s in the development of jet aircraft, and they are also being used in the 2010s in the development commercial crew and cargo launch systems for post-Space Shuttle access to the International Space Station.)

Figure 13-3 Cumulative Financial Results for the First 12 Years (DRM-1, -2 and -3)



Credit: Artemis Innovation Management Solutions LLC (2013)

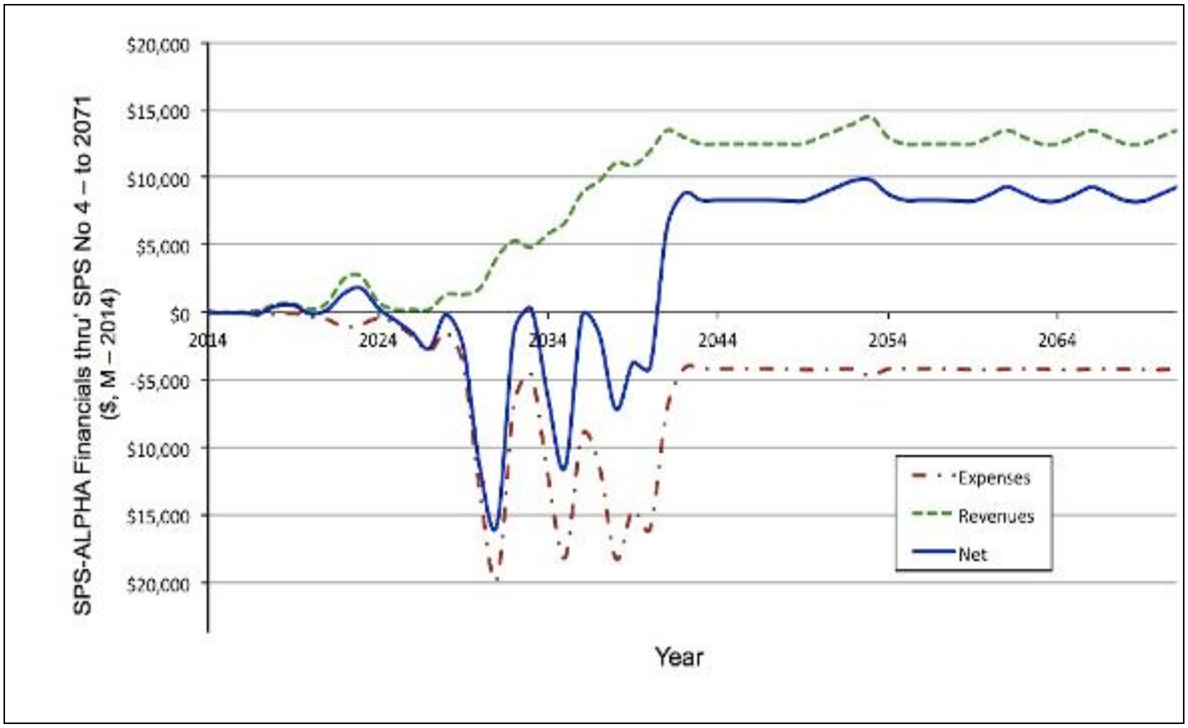
So, if the first six years of an SPS-ALPHA business case looked good, and the first dozen years look even more promising: what about the roughly twenty years that would follow? The deployment of DRM-3 in GEO appears to require more funding and greater risk that would DRM-1 or -2; what would happen after full-scale development and deployment starts?

The Business Case Over 50-Plus Years

Looking beyond DRM-3 deployment to the farther term, sales of power to premium niche markets are projected to begin, followed by the development and deployment of the first full-size Solar Power Satellites. Of particular interest is an integrated scenario that begins in 2014-2015 with technology research and development, and which continues through the deployment of the first several SPS-ALPHA platforms at full scale (i.e., each providing 2 GW to Earth). Figure 13-4 presents the results of an integrated financial analysis through 2071, assuming that the deployment of SPS platforms ends with the fourth 2 GW class (DRM-5) satellite.

The most critical assumption in the figure is this: the wholesale prices for electricity are held fixed at 2013 levels. This is far more optimistic than even “Scenario Zero,” which we discussed in Chapter 2. No known forecast predicts that energy costs will not increase during the next five decades and more. In the section that follows, we will take a look at the long-range economic prospects for Space Solar Power and SPS-ALPHA, including (a) “2013 Forever;” (b) Scenario Zero; and) (c) Scenario Gamma.

Figure 13-4 Integrated Financial Results Through the First Four SPS-ALPHA @ 2GW

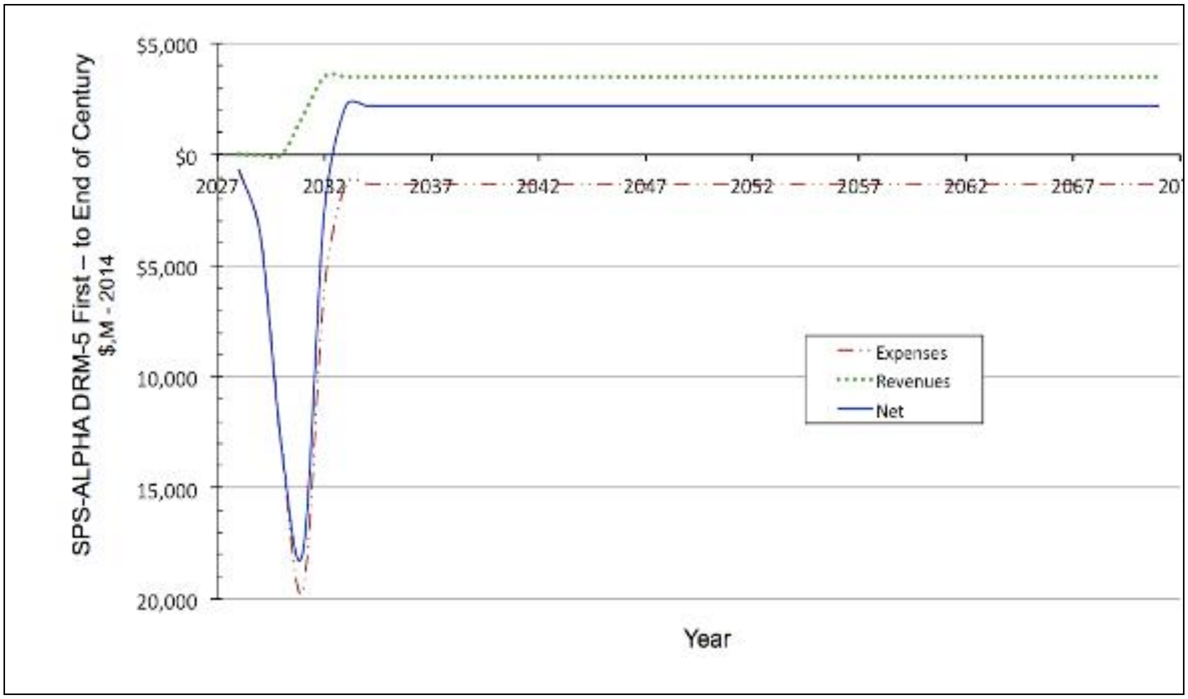


Credit: Artemis Innovation Management Solutions LLC (2013)

The major "dips" in the expenses curve shown in Figure 13-4 – not surprisingly – reflect the necessary costs to manufacture and deploy the several SPS-ALPHA platforms. The single largest necessary expense that is not included among these major "dips" is for the development of reusable space transportation systems during the years between 2019 and 2024. As we discussed in Chapter 7, there are a number of companies (and some government agencies) that are well positioned to develop RLVs and provide low cost Earth-to-orbit (ETO) transportation once a market is established. It is assumed in this discussion that one or more such systems will become available, and that it would not be necessary for a venture delivering Space Solar Power to also become a ETO service provider.

Economics for a Typical Full-Scale SPS-ALPHA. The basic building block for the case described above – involving some four full-scale (i.e., 2 GW capacity) Solar Power Satellites – is that of a single SPS. Figure 13-5 presents the results for a single platform of this size, in which the initial significant cost of deployment (about $30B) is followed by annual expenses for operations and maintenance, exceeded by annual revenues due to sales in various international markets.

Figure 13-5 Notional Financial Results for a Typical SPS-ALPHA (DRM-5)



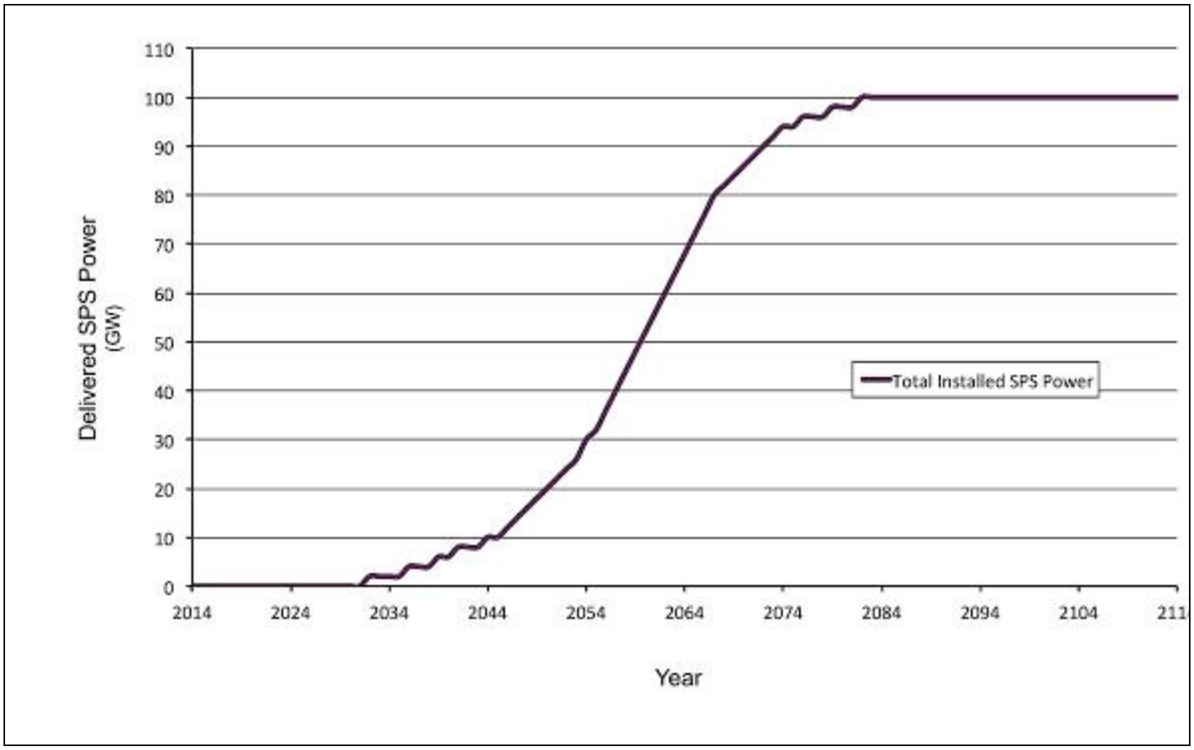
Credit: Artemis Innovation Management Solutions LLC (2013)

As above, the market for this case is the 2013 market, frozen in time, shifted to 2027 and stretched out over 45 years. The key point to draw from the case presented in Figure 13-5 is that, after a single sharp expense for manufacturing and deployment, the conservative technology of the SPS-ALPHA brings in positive revenues almost immediately) and pays for itself in about 15 years.

Over the Next 100 Years

The figure presents a long-term view of all five SPS-ALPHA DRMs, including the advanced technology version of DRM-5. Of course, if only deploying one or just a handful of full-scale platforms, the strategic financial benefits of developing Solar Power Satellites will not be realized. Figure 13-6 presents a “grand-scale” macro-economic view of the SPS-ALPHA with a total capacity of 100 GW of employed terrestrial power, implemented over the next 100 years with a LCOE of less than 9¢/kW-hr. This projected capacity is far less than the market demand we identified earlier (see Table 13-3).

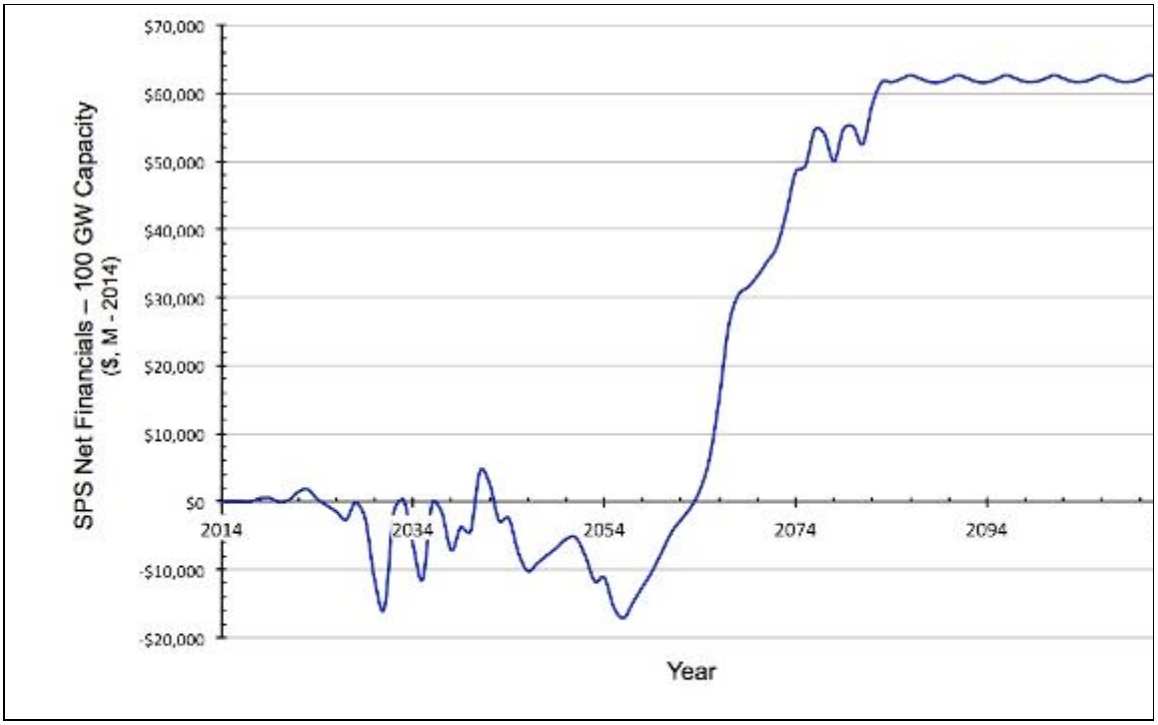
Figure 13-6 100-Year / 100 GW SPS Scenario: Power Deployment Scenario



Credit: Artemis Innovation Management Solutions LLC (2013)

Figure 13-7 presents the associated financial performance for this case, with the highly unlikely projection that the next century will be *exactly like 2013*. Note that in this projection, modest additional technology improvements are included for the platform beyond the initial DRM-5 case) and for supporting space infrastructures. The "ripples" in the financial curve in Figure 13-7 are caused by successive deployments of SPS platforms – at first, one every several years, then one every two years, then one each year, and so on. Ultimately, the net income from this hypothetical SPS industry at a power capacity of 100 GW) reaches roughly $60B per year. Even at this scale, Space Solar Power would still represent only a very small fraction of the total power capacity required for global markets today, much less in 2100. However, this scenario indicates that SPS-ALPHA could readily be economically viable with modest technology advances beyond the current state-of-the-art in the laboratory and a small share of the market. Based on the systems analysis completed during the recent NIAC study (and updated for this discussion), deployment of an initial 100 GW of Space Solar Power capacity during the next 100 years appears entirely achievable. The maximum *net* annual funding requirement (costs versus revenues) never exceeds roughly $15B in a given year, and is typically much less.

Figure 13-7 100-Year / 100 GW SPS Scenario: Annual Economic Results

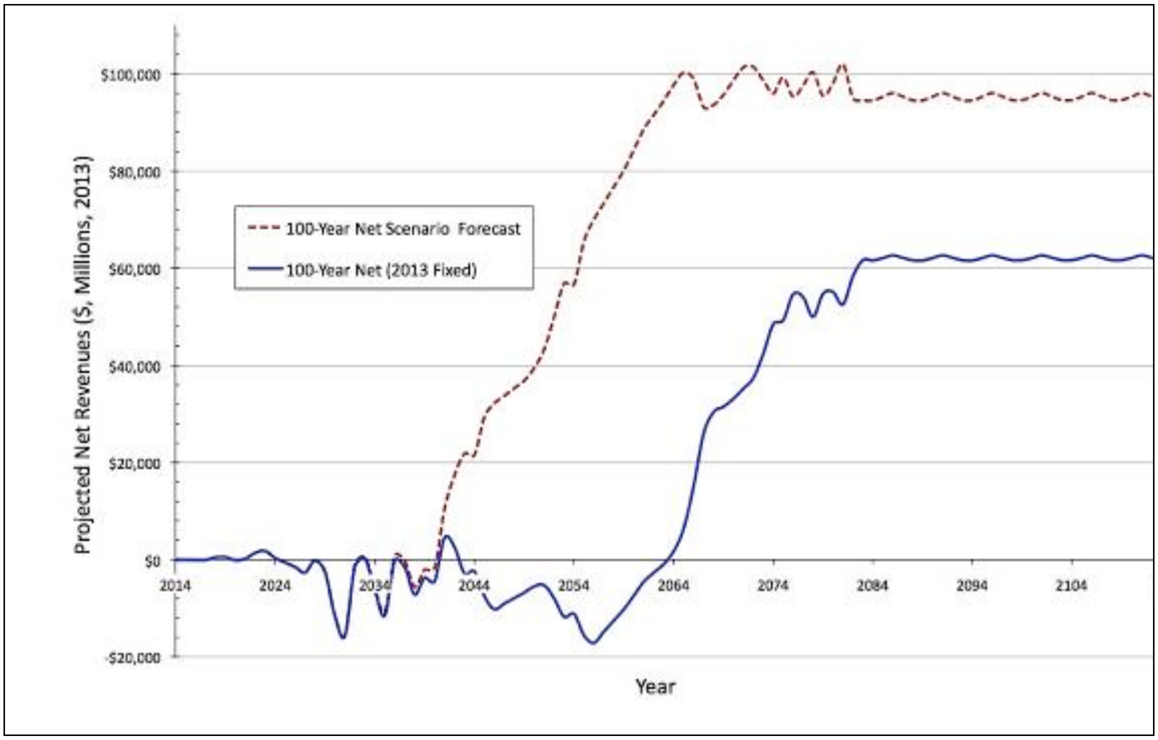


Credit: Artemis Innovation Management Solutions LLC (2013)

Allowing for Uncertainty. For the case of "*Scenario Zero*" as we discussed in Chapters 2 and 12, the best forecast for the remainder of this century is that there will be moderate increases in the wholesale price of electricity, driven – optimistically – by increasing demand and decreasing supply after mid-century. For the other case we've discussed, *Scenario Gamma* it is assumed that policy steps are taken early and successfully to transition global economics to augmented sustainable energy supplies. In both of these cases, the economic opportunities improve in the out-years. In the case of *Scenario Gamma*, there are also early opportunities for government R&D support, although these are not shown. The biggest difference in these two Scenarios comes in the scope of the opportunity: in the cast of *Scenario Gamma*, the market for Space Solar Power is much larger) and begins to grow earlier. However, because we are working to a fixed scope of deployment of SPS-ALPHA platforms (only 100 GW, and deployed over a fixed period of time), neither of these enters into the diagram that follows.

Figure 13-8 illustrates these two alternative futures: “2013 Forever,” and the scenario-based forecast) which includes scope for either *Scenario Zero* (business as usual) or *Scenario Gamma* (sustainable energy early). As we saw in Chapter 2, in both of the other Scenarios, (*Climate Catastrophe*) and *Fossil Fuels Run Out*) the need for Space Solar Power becomes all the more urgent – and the market opportunity all the more attractive.

Figure 13-8 100-Year / 100 GW SPS Scenario: Two Cases



Credit: Artemis Innovation Management Solutions LLC (2013)

In both cases, the curve illustrates the net revenues (including deployment and O&M costs annually) for a total of some 50 Solar Power Satellites, each providing 2 GW of power. The net revenues over the century are clearly positive in both; in the 2013 case, the net is almost $2.5 Trillion over the century, and in the Scenario-based forecast case, the net is slightly more than $6 Trillion (both in 2013 dollars). For each SPS-ALPHA platform, of course, the revenues approximately follow the life cycle projections as illustrated for a single platform in Figure 13-5. Is this a lot? Yes and no. As we saw above in the case of Scenario Zero, the projected revenue opportunity is about 770 GW, of which the analysis above only supports 100 GW, or about 13% -- which works out to only 0.18% of the total global demand for energy. As a coincidence, in the case of Scenario Gamma, where the projected market opportunity is about 2100 GW, of which the same 100 GW is only a bit less than 5%, or – in a happy coincidence, again about 0.18% of the total global demand for energy.

If Space Solar Power were to be developed, there is a tremendous opportunity even at a tiny share of the global energy market this century.

Closing Observations

The business case for Space Solar Power is very promising. Based on the best analysis to date, SPS-ALPHA should be capable of delivering baseload power within global markets at a levelized cost of electricity (LCOE) of less than 10¢ per kilowatt-hour in the mid term (say, 15-20 years hence) and less that that in the far term. Before then, the interim system-level demonstrations on the path to SPS-ALPHA represent significant market opportunities in and of themselves, particularly for a range of important and ambitious space missions and markets, including both government and commercial applications. For three different options, the hyper-modular architecture has a positive economic performance in the near-term and over the coming century. Based on the best information available, SPS-ALPHA appears to be a viable – perhaps critical – new option for terrestrial energy.

At present, power in space costs upwards of $50 to $100 per kilowatt-hour or more: roughly 1,000-times more than the cost of energy on Earth. It seems unimaginable that anything ambitious can be accomplished in space – no resources development, manufacturing, or a settlement on Mars or the Moon – while the cost of energy remains so outrageously high.[9] However, if the cost of energy *in* space can be reduced to less than 10¢ per kilowatt-hour, and the cost of access to space is less than $500 per kilogram, then *anything* becomes possible. With such capabilities, hundreds to thousands of tons of equipment and logistics could be sent anywhere in the inner Solar System at a tiny fraction of the cost of doing so today. Humanity could truly become a multi-planet species. And, the systems that would make SSP possible would also enable a robust planetary defense, eliminating the danger to Earth from all but the largest and most unexpected impact hazards.

Given the diversity and strength of the energy, government, and commercial space markets) and the diverse prospects for space mission applications, it may be argued: *why* ***wouldn't*** *we pursue Space Solar Power*?

[13-1] See: http://www.neatorama.com/2012/10/10/FedEx-Founder-Gambled-His-Last-5000-at-a-Blackjack-Table-to-Stave-Off-Bankruptcy/; Fred Smith, of course, went on to found Federal Express.

[13-2] Tauri Group, for the Satellite Industry Association; "State of the Satellite Industry Report" (Washington, DC). June 2013.

[13-3] See: http://www.thespacereview.com/article/533/1.

[13-4] See: http://kai.gemba.org/pdf/space/prometheus.pdf.

[13-5] See: http://www.gao.gov/assets/250/245477.pdf.

[13-6] As before, please recall that the details, although they are plausible and – hopefully – consistent with projections by various organizations, are not presented as "real." (Who knows what the future will really hold 100 years from now?) So, I am not arguing that they represent actual future prices, which may be higher or lower; they are only intended to frame the discussion of future market opportunities.

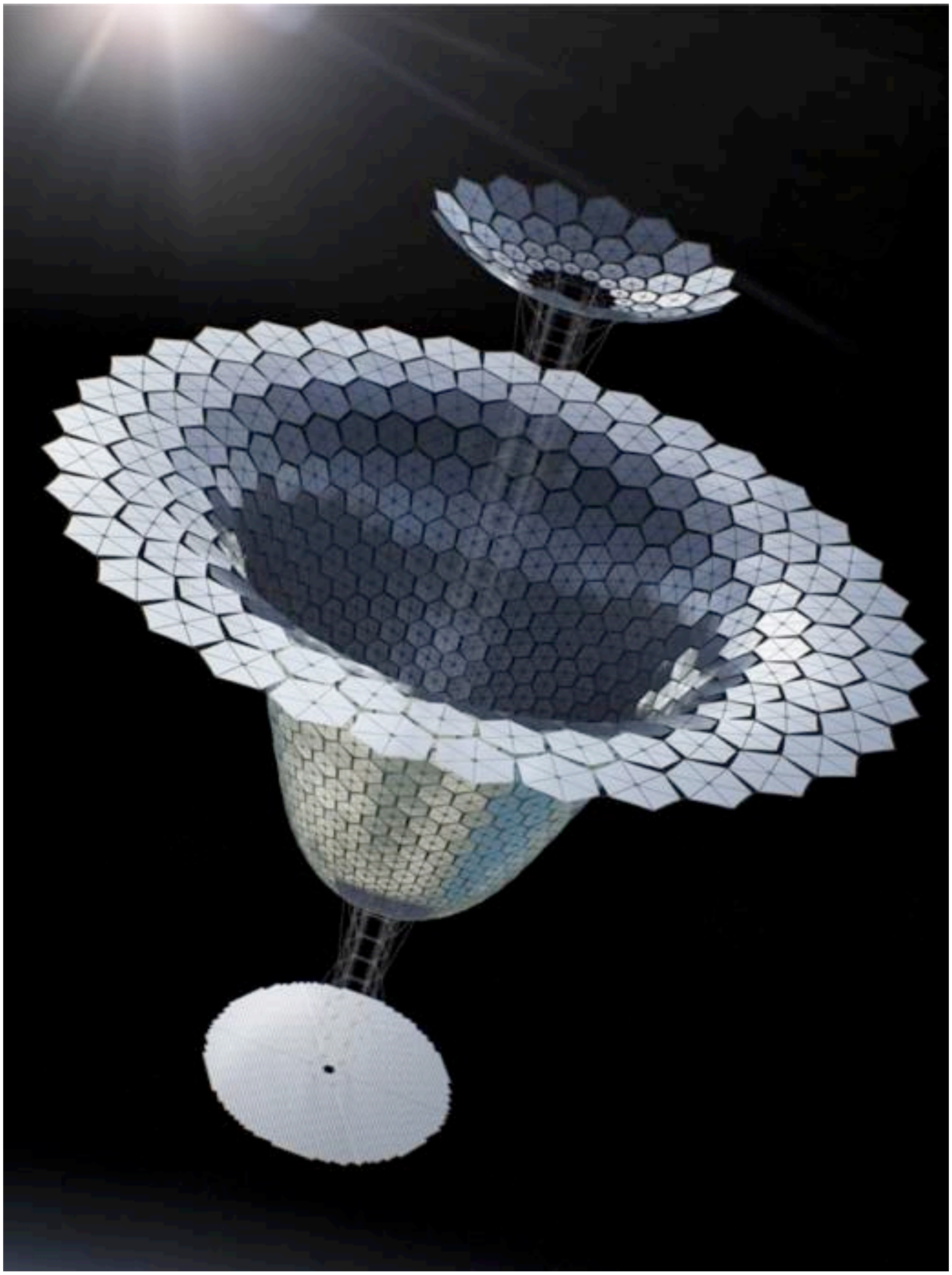
[12-7] This overall projection was explained in Chapter 2.

[12-8] This overall projection was explained in Chapter 2.

[13-9] To draw a personal comparison, at $100 per kilowatt-hour, the electricity used in my single family, rural home in the U.S. would cost about $500,000 annually, more than the value of the house!

Part V

The Path Forward



Chapter 14

Integrated Technology Readiness and Risk Assessment

> *"Where a calculator on the ENIAC is equipped with 18,000 vacuum tubes and weighs 30 tons, computers in the future may have only 1,000 vacuum tubes and weigh only 1.5 tons."*
>
> *Popular Mechanics*
> *(March 1949)*

Introduction

At the end of Chapter 13, a critical question was posed: given the benefits and the economics, why wouldn't we pursue Space Solar Power? One reason would be if the technologies needed just weren't available. In that case, SSP would be little more than interesting Science Fiction. Fortunately, that's not the case.

A critical step in developing any new system is verification that the needed technologies are sufficiently mature to begin – and that they can meet the performance and cost requirements of the system.[1] Various groups, including the 2008-2011 International Academy of Astronautics (IAA) assessment of SSP) and the 1999-2000 evaluation of NASA's technology roadmap for Space Solar Power by the US National Research Council (NRC), have validated that the SPS concept is technically feasible. The IAA study also examined in very broad strokes the maturity (i.e., technology readiness levels) of specific technologies needed for three different types of Solar Power Satellites, including a modular microwave WPT concept) such as SPS-ALPHA. (These three – and others – were discussed in Chapter 4.)

Although a great deal of additional work is needed to refine SPS systems designs and better identify needed technology, the preliminary 2011-2012 NIAC Phase 1 study found that the technologies required to begin SPS-ALPHA development have already been proven in the laboratory (although not for this specific system architecture, of course). Many are already in use on Earth or in other space applications.

This Chapter presents an integrated technology readiness and risk assessment (TRRA) for SSP, focusing on SPS-ALPHA) and beginning with a summary review of the most important technology challenges.

Technology Challenges for Space Solar Power

The strategic technical hurdles that must be overcome to realize the vision and the benefits of Space Solar Power include:

- Reduced system mass;
- Efficient electronic devices at high temperature;
- Efficient and flexible power management and distribution;
- Effective low-mass thermal management;
- Large space system assembly, integration, maintenance, and repair;
- Large-scale, extremely low-cost manufacturing of space-qualified systems; and
- Affordable space transportation.

A host of additional issues could be identified readily – each of which is important to the realization of future SSP systems. For example, guidance navigation and control – particularly attitude control (and momentum control systems) – are vitally important; another issue is that of system and subsystem reliability and lifetime; and so on. The following sections examine the technological hurdles listed above in somewhat greater detail, including potential approaches to their solution.

Reduced System Mass

Ultimately, the mass of the system (which is a consequence of the hurdles that follow) will determine the viability of SSP for terrestrial markets. Because SPS concepts involve by their nature the deployment of exceptionally large systems and because of the challenge of space transportation (discussed later), a fundamental barrier to realizing SPS in the future is that of reducing system mass. There are many approaches that might be pursued to accomplish that goal.

The use of large, lightweight, thin-film reflectors is one very promising approach. In this case, the large reflectors could be used to redirect and concentrate incoming sunlight onto the platform solar arrays. These large structures may be used in concepts such as the NASA-defined Integrated Symmetrical Concentrator (ISC), the earlier sandwich approach advocated by Japan’s Prof. Nobuyuki Kaya, or in SPS-ALPHA. In addition, a variety of other component technology advances – some of which are discussed in paragraphs that follow – could substantially improve system mass. Continuing progress in new materials looks very promising, particularly in future applications of the rapidly evolving field of carbon nanotubes (CNT) and related technologies.

Essentially all of the technology challenges that follow – device efficiency, power management and distribution, thermal management, and so on – are related to the challenge of reducing SPS platform mass while maintaining or improving system performance.

High Efficiency Electronic Devices At High Temperature

Throughout SSP systems concepts, the efficiencies of individual devices – beginning with cells in the solar array and ending with the receiver on Earth – determine the ultimate viability of the system. Moreover, as we discussed in Chapter 4, by the physics of waste heat radiation (i.e., the Stefan-Boltzman equation) the hotter an object, the more waste heat can be dispersed into space. Unfortunately, the efficiency of currently available electronic devices drops quickly as temperature increases above some specific point – and of course as the efficiency drops, more waste heat is produced, raising temperatures still further. There are two primary functional areas in which improved device-level efficiencies at higher temperatures are needed: first, within solar energy conversion systems, and second, within the solid-state devices of the WPT system itself.[2]

Great progress has been achieved during the past thirty years in all of these areas. For example, photovoltaic (PV) cell efficiencies have progressed from about 10% efficiency (1979) to 30% efficiency or more (2010). Also, solid-state electronic devices, such as power amplifiers for WPT, have advanced from efficiencies in the 20-30% range (1979) to 70%-80% today. However, these devices are still limited to relatively low temperatures – limiting their effectiveness in the context of the strategies mentioned that might use concentrated sunlight approaches to reduce the overall mass of the system. As a result, in order to reduce the mass of future high power SSP systems, operating at higher than ambient temperatures – at least in some parts of the system – is strongly desired.

As mentioned, over the past 10 years dramatic improvements have been achieved in the efficiency of photovoltaic (PV) devices and systems. Significant advances have been achieved through the use of multi-bandgap PV cells. The concentrator photovoltaic (CPV) stretched-lens array (SLA) created by Mark O'Neill of ENTECH, Inc. and his colleagues as part of NASA's SERT program in the late 1990s provides one elegant example of how such improvements may be integrated into a system. In this case, sunlight is locally concentrated, converted (by multi-bandgap PV cells at high efficiency), and residual waste heat efficiently dissipated. Work also continues at the basic cell level with research into the possible application of new quantum-scale structures (e.g, quantum dots or use of carbon nanotubes (CNT) in future PV cells.

On the electronics side, efficiencies have also increased greatly. In the late 1970s, a solid-state device microwave amplifier typically had an efficiency (DC-to-RF) of approximately 20%. At present, solid-state amplifiers with efficiencies of 70% are available – a huge improvement. (It is because of this improvement in device efficiencies that options such as the retro-directive phased array WPT have become possible.)

Efficient and Flexible Power Management And Distribution

The 1979 SPS Reference System resolved the problem of power management and distribution (PMAD) by assuming that the system – beginning at the solar array level – could be operated at a very high voltage (thus reducing the overall mass of the platform dramatically). This approach now appears not to be viable due to space environmental effects (i.e., expected micrometeorite impacts and induced array discharges). In the case of large, distributed platform concepts (e.g., the NASA "SunTower" design, in which solar power generation is separated from WPT systems), the application of high-temperature superconducting power cabling is one potential technology that might allow the use of lower voltages while still achieving relatively low cable mass.

Sandwich-type concepts such as SPS-ALPHA solve this problem neatly by placing solar power generation immediately next to WPT systems, allowing lower voltage PMAD to be used. However for all types of systems, improvements in the mass of the PMAD are needed, as well as increased flexibility in reconfiguring the PMAD, for example in case of damage. (The modular wireless micro-inverter architectures that have emerged in recent years for ground-based PV arrays are an excellent example of the type of approach needed for SPS PMAD.)

Effective Low-Mass Thermal Management

As we discussed previously, because the system and the elements comprising it will not be perfectly efficient, the disposition of waste heat will be a problem of tremendous importance. The challenge of thermal management is a direct consequence of the failure to advance in many of the other SPS platform technical areas discussed above. The heat that remains after wireless power transmission must be dissipated. The waste heat generated by the converters, switches, and cables in the PMAD systems also must be dissipated. The waste heat that is generated from inefficiencies in solar energy conversion – particularly in the case of dynamic energy conversion options – must be dissipated. Throughout the notional designs of future large SPS systems, the inefficiencies of the concepts and technologies that we have today lead to what could be a "crisis" in thermal management and waste heat rejection.

A successful strategy for dealing with SSP thermal management issues will be three-fold. First, one must wherever possible improve the operational efficiency of component devices and subsystems in order to reduce the amount of waste heat with which we must cope. Second, one must reduce the mass and improve thermal management efficiency and heat rejection technologies wherever possible. And finally, one must seek new, more innovative approaches to SPS systems and find clever ways to work around the shortcomings of current devices and technologies.

As we discussed in Chapter 4, one of the most promising future SSP systems-level concepts is that of a "sandwich-type" SPS, such as SPS-ALPHA. In this case, incoming sunlight is redirected by large optical systems (in a fashion quite similar to the ISC mentioned previously) onto the back of an integrated planar PV-PMAD-WPT structure. The elegance of the concept lies in its local management of power, and the exceedingly short distance (perhaps a few centimeters) for transporting electrical energy from PV array to WPT emitter. Unfortunately, the amount of concentration that can be used is at present quite limited by the temperature increases that would result from high concentration. Although SPS development can begin with the currently available concepts, new thermal management systems and technologies are still needed that resolve these issues and enable a higher concentration ratio. One area of promise is that of MEMS (micro-electrical-mechanical systems): the idea of locally embedded heat pipes, heat pumps and refrigerators with other system elements (e.g., solid state transmitters and PV arrays, providing a line of attack on the thermal management problem that may be fruitful.

Large System Assembly, Integration, Maintenance And Repair

Future SPS would be extraordinarily large – many times larger than the International Space Station (ISS) and intended to operate for many decades, if not indefinitely; certainly many times longer than today's communications satellites. SPS would constitute the largest of all future space systems. In the 1970s, it was expected that the problem of constructing and maintaining these systems would be resolved by placing huge construction platforms (involving 100s of astronauts) in LEO and GEO. However, these conceptual solutions were projected to involve initial costs of more than $300B-$1,000B ($, FY 2013) before the first commercial kilowatt-hour of energy could be delivered. Today, a host of advances in computing, software, sensing and materials make possible robotic systems of previously unbelievable complexity and capability. As a result, a novel approach is now possible for SPS: supervised semi-autonomous self-assembly of the SPS where the platform is designed to facilitate such in-space construction. This is the approach that SPS-ALPHA embodies.

Progress toward this capability has been slow for space applications but it has been rapid in the laboratory. For example, Figure 14-1 below presents several generations of six-legged robots developed by NASA at the Jet Propulsion Laboratory (JPL) during the late 1990s. These systems – known as “Hexabots” due to their six-limbed architecture – represented impressive capabilities for their era. However, these small robots were limited in that they typically operated independently from other systems.

Figure 14-1 Several Generations of NASA/JPL “Hexabot” from the mid-1990s

Image Credit: NASA / JPL

In contemporary technology developments (i.e., circa 2013), cooperative robotic behaviors have been successfully demonstrated that allow large and complex structures to be easily assembled in the laboratory. For example, large and complex structural assembly by autonomous teams of free-flying helicopters has been recently demonstrated.[3] The key to translate such accomplishments to SPS platform R&D and deployment in the coming decade is the coordinated design and development of the assembly robotics and of the structural systems to be assembled.

Large-Scale, Low-Cost Manufacturing Of Space-Qualified Systems

We spoke about hardware costs in Chapter 6, and again in Chapters 10 and 13. As we saw, even at commercial aviation hardware cost levels of about $1000 per kg – which is much less than typical space hardware costs – large SPS will not be economically viable for baseload power. Costs consistent with large-scale consumer products manufacturing must be achieved if commercial SPS are to be viable. In SPS-ALPHA, the solution to this problem is to employ a "hyper-modular" architecture in which a very large number of essentially identical modules comprise a single large SPS platform. However, the success of this architecture will depend on the modules being amenable to automated mass production, while incorporating materials and components that are robust enough for operation in space.

Affordable Space Transportation

Very low cost access to space, including transportation from Earth to orbit (ETO) as well as transportation in space, is a fundamental hurdle for future SPS platforms. Even using the most aggressive assumptions regarding technological advances in the field of materials, the mass associated with meaningful SPS – both an individual satellite and a global constellation – will be such that transportation costs will represent a substantial contribution to total installed cost for the system. One challenging issue involves transportation in space. In particular, the conundrum is that in-space transportation systems that have high thrust – and therefore move quickly from orbit to orbit – are not fuel-efficient. And conversely, highly fuel-efficient propulsion systems have low thrust – and involve long transit times. As a result, the SPS architect must confront either high costs to launch fuel for in space transportation or deal with long transit times and poor utilization of the fixed capacity.

In addition to the common technical challenges discussed above, there is one more special topic that merits inclusion here: the possible use of extra-terrestrial materials in Space Solar Power systems.

Special Topic: Extraterrestrial Manufacturing Of SSP Systems

Many of the challenges of Earth-to-orbit and in-space transportation costs might be resolved through the successful use of extraterrestrial materials in future SSP systems. The advantage comes in part from the much lower energy requirements to escape from small bodies or the

Moon (as we discussed in Chapter 7). Also, there is the possibility of launching SPS elements electromagnetically from the Moon at very low cost rather than chemically from the Earth (see the previous discussion of space transportation). These approaches seem to hold significant promise for the far term, particularly once an SPS industry has been established. However, the infrastructure requirements of in-space resources utilization (ISRU) and in-space manufacturing would seem – if placed in series with the initial development and deployment of SPS – to represent yet another barrier to programmatic viability.

However, based on studies and research to date, these issues appear tractable through technology development and engineering in the context of the solutions to the more fundable hurdles cited above. As we touched upon in Chapter 8, the idea of 3D printing systems (aka, additive manufacturing) seems especially promising.

Technology Readiness and Risk Assessment Methodology[4, 5]

It is important to understand both the current maturity of the technology that will be needed and the risk that R&D programs will not complete their development as scheduled. An integrated Technology Readiness and Risk Assessment (TRRA) requires the decomposition of the SPS-ALPHA concept into functional areas corresponding to key technology requirements and determination of three key R&D metrics for each:

(1) The technology readiness level (TRL) for key systems functions;

(2) The projected "R&D degree of difficulty" (R&D^3) for the program required to mature those technologies to TRL 6 by the timeframe at which system development for each stage in the roadmap is to be initiated; and.

(3) "Technology need values" (TNV) for each of the technologies assumed in the proposed approach to accomplish those functions.

Technology Readiness Levels

The Technology Readiness Level (TRL) scale developed by NASA is the standard method of evaluating and communicating the status of technology maturation for a particular systems application. The TRL scale is now used broadly across the US Government, in industry, and (increasingly) internationally. Table 14-1 summarizes the standard definitions of the TRL scale as used in this assessment of SPS-ALPHA technologies.

Table 14-1 Standard Technology Readiness Level (TRL) Definitions

READINESS LEVEL	DEFINITION	EXPLANATION
TRL 1	Basic principles observed and reported	Lowest level of technology readiness. Scientific research begins to be translated into applied research and development.
TRL 2	Technology concept and/or application formulated	Once basic principles are observed, practical applications can be invented and R&D started. Applications are speculative and may be unproven.
TRL 3	Analytical and experimental critical function and/or characteristic proof-of-concept	Active research and development is initiated, including analytical / laboratory studies to validate predictions regarding the technology.
TRL 4	Component and/or breadboard validation in laboratory environment	Basic technological components are integrated to establish that they will work together.
TRL 5	Component and/or breadboard validation in relevant environment	The basic technological components are integrated with reasonably realistic supporting elements so it can be tested in a simulated environment.
TRL 6	System/subsystem model or prototype demonstration in a relevant environment (ground or space)	A representative model or prototype system is tested in a relevant environment.
TRL 7	System prototype demonstration in a space environment	A prototype system that is near, or at, the planned operational system.
TRL 8	Actual system completed and “flight qualified” through test and demonstration (ground or space)	In an actual system, the technology has been proven to work in its final form and under expected conditions.
TRL 9	Actual system “flight proven” through successful mission operations	The system incorporating the new technology in its final form has been used under actual mission conditions.

Another measure used in this technology readiness assessment is a comparison of the current TRL of a given technology to the level of maturity that is desired at the beginning of system development; this is the "*Delta-TRL*."

ΔTRL. The Delta-TRL (ΔTRL) is a derived measure of the level of maturity *relative to* a particular goal in a planned R&D program. ΔTRL is simply the difference in TRLs between the current level of maturity of a particular technology and the TRL desired by a particular point in time in the future. For example, if the desired TRL is TRL-6 and the current TRL is TRL-3, the Delta-TRL is ΔTRL=3. In this example, ΔTRL=3 corresponds the challenge of technology that is currently in the laboratory, proof-of-concept level (TRL=3) and which must advance to a system-level prototype demonstration in an operationally relevant environment (TRL=6). Each step represents another level of developmental maturity – hence, more steps are equivalent to greater R&D investment over a given length of time.

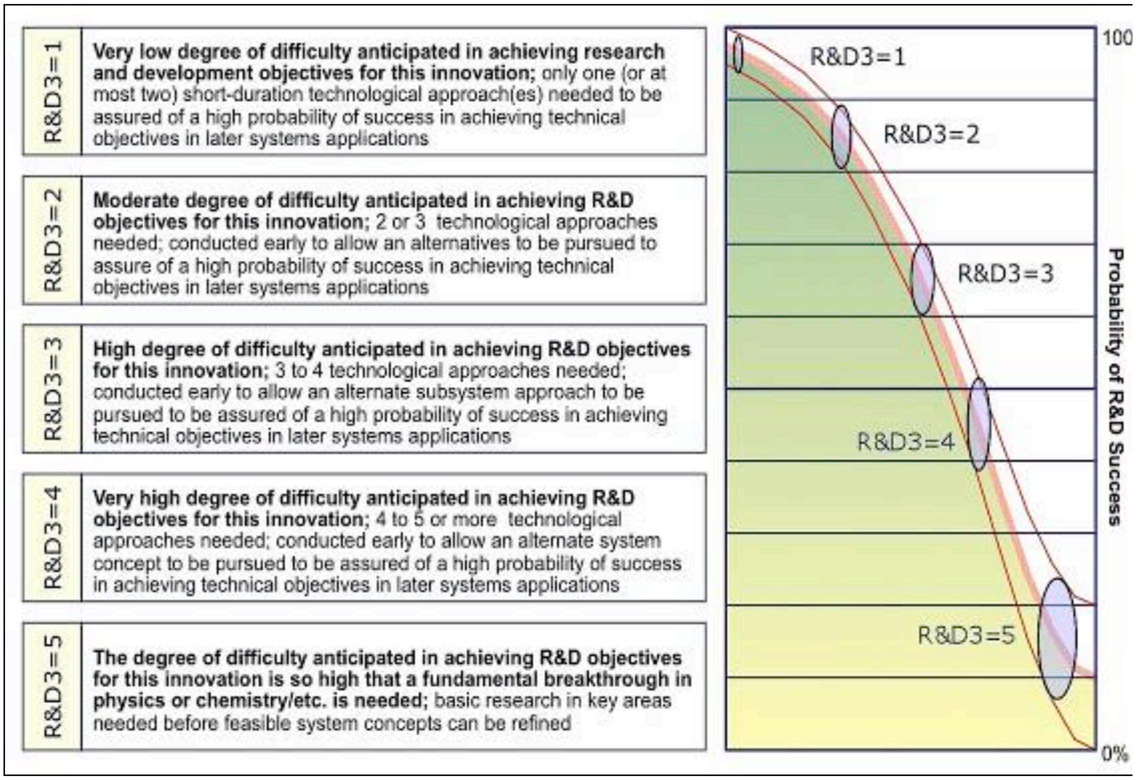
Research and Development Degree of Difficulty

TRL's are a systematic, non-discipline specific metric/measurement system that supports assessments of the maturity of a particular technology and the consistent comparison of maturity between different types of technology. Yet another measure – the "Research and Development Degree of Difficulty" (R&D^3) – is a way of characterizing the uncertainty (i.e., probability of success and/or failure) of the planned technology development effort. (See Figure 14-1.) The following paragraphs provide definitions of each of the levels in the R&D^3 scale.

A measure of how much difficulty can be expected in the maturation of a particular technology can be very useful as a complement to the standard TRL scale. This is what "R&D^3" provides for an integrated technology readiness and risk assessment.

R&D^3 = 1. An R&D^3 of "1" corresponds to an expected degree of difficulty in achieving research and development objectives that is low; in other words, the probability of success is high enough to assure that with only one or two alternative technological approaches a given program can realize a high probability of achieving a given set of R&D objectives. Generally speaking, an R&D^3 of 1 would correspond with moderate to high level of TRL; however, there may be cases in which a low TRL technology could have an R&D^3 of "1" because the R&D path requires no obvious technical hurdles, special facilities, or unusual testing environments.

Figure 14-1 Research and Development Degree of Difficulty (R&D^3)



R&D3=1	**Very low degree of difficulty anticipated in achieving research and development objectives for this innovation;** only one (or at most two) short-duration technological approach(es) needed to be assured of a high probability of success in achieving technical objectives in later systems applications
R&D3=2	**Moderate degree of difficulty anticipated in achieving R&D objectives for this innovation;** 2 or 3 technological approaches needed; conducted early to allow an alternatives to be pursued to assure of a high probability of success in achieving technical objectives in later systems applications
R&D3=3	**High degree of difficulty anticipated in achieving R&D objectives for this innovation;** 3 to 4 technological approaches needed; conducted early to allow an alternate subsystem approach to be pursued to be assured of a high probability of success in achieving technical objectives in later systems applications
R&D3=4	**Very high degree of difficulty anticipated in achieving R&D objectives for this innovation;** 4 to 5 or more technological approaches needed; conducted early to allow an alternate system concept to be pursued to be assured of a high probability of success in achieving technical objectives in later systems applications
R&D3=5	**The degree of difficulty anticipated in achieving R&D objectives for this innovation is so high that a fundamental breakthrough in physics or chemistry/etc. is needed;** basic research in key areas needed before feasible system concepts can be refined

<u>R&D^3 = 2</u>. An R&D^3 of "2" reflects a no more than a moderate expectation of difficulty in achieving research and development objectives. Not less than two or three alternative technological approaches should be pursued, if a given program wishes to have a high probability of achieving a given set of R&D objectives. Generally speaking, an R&D^3 of 2 would correspond with a moderate to higher level of TRL, although there may be cases in which lower TRL technologies reflect an R&D^3 of "2" due to details of expected R&D.

<u>R&D^3 = 3</u>. An R&D^3 of "3" corresponds to an expected degree of difficulty in achieving research and development objectives that is high enough that substantial R&D is needed. As a result, if a given program wishes to have a high probability of achieving a given set of R&D objectives, then not less than three or four technological approaches need to be pursued. In this case, applied research may be needed before detailed designs for technically feasibility system concepts can be developed. Generally speaking, an R&D^3 of 3 corresponds to a low to moderate TRL.

R&D^3 = 4. An R&D^3 of "4" represents the expectation that there will be a very high degree of difficult in achieving research and development objectives. As a result, if a given program wishes to have a high probability of achieving a given set of R&D objectives, then not less than four or five technological approaches need to be pursued. Also, in this case, R&D should be conducted early enough to allow for significantly different alternative system concepts to be pursued based on the results of the R&D effort. Generally speaking, an R&D^3 of 4 would correspond with a low value to moderate value of TRL.

R&D^3 = 5. An R&D^3 of "5" corresponds to an expected degree of difficulty in achieving research and development objectives that is so extremely high that a fundamental breakthrough in physics, chemistry, etc., is required. In this case, basic research is clearly needed before technically feasibility system concepts can be defined in detail. Generally speaking, an R&D^3 of 5 corresponds with a very low value of TRL.

Technology Need Value

The Technology Need Value (TNV) is a measure of the importance of a particular technology (including a set of figures of merit) to one or more specific system concepts in a targeted application. Some of the technologies applied in a system concept are critical to the functional characteristics of the concept; these are "enabling." Other technologies are "enhancing" to varying degrees and might be replaced with other technologies with only modest changes to the performance, cost, etc., of the system to be developed. The Technology Need Value (TNV) is a qualitative measure of this factor. The five TNV values used in the TRRA presented here include the following.

TNV-1. In the case of a TNV of "1," the technology R&D effort *is not critical at this time* to the success of the program—the advances to be achieved are useful for some cost improvements; however, the information to be provided is not needed for management decisions until the far-term.

TNV-2. A TNV of "2" represents a technology effort that is *useful* to the success of the program—the advances to be achieved would meaningfully improve cost and/or performance; where the information to be provided is not needed for management decisions until the mid-to-far term.

TNV-3. For a TNV of "3", the technology effort is important to the success of the program—the advances to be achieved are important for performance and/or cost objectives and the information to be provided is needed for management in the near- to mid-term.

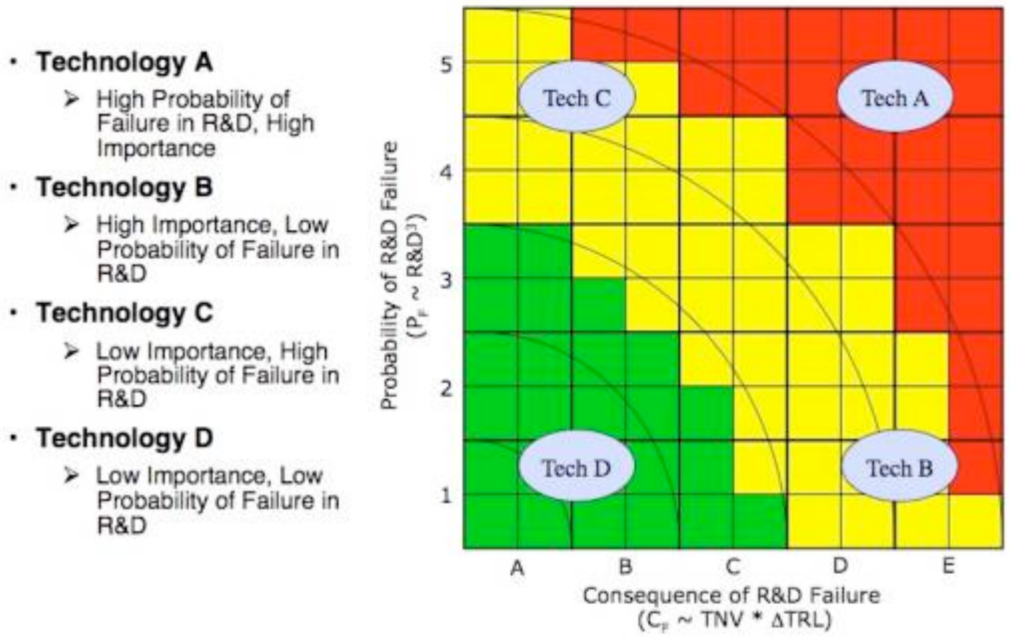
TNV-4. A TNV of "4" corresponds to a case in which the technology effort is very important to the success of the program; the advances to be achieved are enabling for cost goals and/or important for performance objectives and the information to be provided would be highly valuable for near-term management decisions.

TNV-5. In this case, the technology effort is critically important to the success of the program at present; the performance advances to be achieved are enabling and the information to be provided is essential for near-term decisions.

Integrated Technology Risk Matrix

The three technology management metrics described above – TRL, R&D^3 and TNV – allow the consistent assessment of (1) the maturity of a new technology, (2) the expected uncertainty inherent in the R&D program needed to complete maturation, and (3) how important that new capability would be to the system that is the ultimate goal. However, sometimes it can be difficult to look at columns of numbers in a table and glean the strategic meaning of the results: a synthesis of the detailed results into some overarching visualization is also useful. To meet this need, a technology readiness and risk assessment risk matrix may be constructed. See Figure 14-2 for a generic integrated TRRA risk matrix.

Figure 14-2 Generic Integrated TRRA Risk Matrix



For several of the major stages in the planned systems-technology development roadmap of the SPS-ALPHA, a preliminary technology readiness and risk assessment was developed as part of the NIAC Phase 1 project and an integrated TRRA matrix constructed; somewhat updated versions of these results are presented in the section that follows.

Integrated Technology Readiness and Risk Assessment for SPS-ALPHA

Technology Requirements Overview

As we've discussed, no breakthroughs are required to pursue SPS-ALPHA: no new physics or chemistry, no discoveries on the order of carbon nanotubes (CNT) or high-temperature superconductors (HTS). However, a diverse array of technologies that are not yet applied in space systems will be needed to accomplish the SPS-ALPHA architecture. Table 14-2 provides an overview of the generic technology requirements for each of the several modules that comprise SPS-ALPHA. The following are brief descriptions of the more important technologies that are needed.

Low-Mass / High-Strength Structural Materials / Systems. Although SPS-ALPHA can be implemented with conventional materials (such as aluminum), novel structural systems are needed. Also, materials not yet commonly used in space (for example, composites that embody CNT materials) but which may already be in use in terrestrial applications could be very useful in realizing economically viable, low mass systems.

High-Aspect Ratio / High-Strength / Low-Mass Deployable Beams. High aspect ratio, low-mass deployable beams represent a special, architecture-level technology requirement for SPS-ALPHA, and would form the critical interconnects for the structure. Various systems of this type have been used for many years in space systems (for example, to deploy sensitive instruments away from the main body of a science spacecraft); however, much larger systems are required for SPS.

Low-Mass / High-Reflectivity Thin-Film Reflectors. There have already been numerous tests (several in space) of various relevant thin-film reflectors. A key requirement for SPS-SLPHA is to realize these systems in larger sizes and with high surface quality (i.e., flatness).

Robust / Highly-Reliable Mechanisms / Actuators (& Related Tribology). Although the mechanisms of SPS-ALPHA are largely independent, there are nevertheless literally millions of them! (There are far more than have ever been attempted in a space system, or terrestrial system for that matter.) As a result, reliable and durable mechanisms and actuators with minimal friction over long periods of time are needed.

Table 14-2 Crosswalk of Technology Requirements to SPS-ALPHA Modules

	HexBus	Interconnects	HexFrame Structural Module	RDM Module	SPG Module	WPT Module	PAC Module	MARE Systems
Low-Mass / High-Strength Structural Materials / Systems	✓	✓	✓	✓	✓	✓		
Low-Mass / High-Reflectivity Thin-Film Reflectors			✓	✓				
Robust / Highly-Reliable Mechanisms / Actuators (& related Tribology)	✓	✓	✓	✓			✓	✓
High-Aspect Ratio / High-Strength / Low-Mass Deployable Beams			✓	✓				
Radiation / SEU /Latch-Up Tolerant Electronic Devices	✓	✓	✓	✓	✓	✓	✓	✓
High-Temperature / High-Efficiency Electronic Materials	✓	✓			✓	✓	✓	
Space-Based WiFi / Wireless Communications Networks	✓	✓						✓
High-Efficiency / Low Mass Solar Cells / Arrays	✓				✓			
High-Efficiency / Low-Mass Retro-directive WPT w/ High-Efficiency Amplifiers						✓		
Low-Mass / Moderate Temperature Thermal Management	✓	✓		✓	✓	✓	✓	✓
Modular Reconfigurable Power Management & Distribution	✓	✓			✓	✓	✓	✓
High-Efficiency / Moderate-Thrust Electric Propulsion							✓	
Highly-Autonomous Systems / Reconfigurable Avionics	✓	✓				✓	✓	✓
Autonomous Robotics / Manipulators (in Structured Environments)		✓	✓	✓				✓
Autonomous Guidance, Navigation and Control							✓	✓

Radiation / SEU /Latch-Up Tolerant Electronic Devices. Long-lived SPS-ALPHA systems must be capable of enduring and recovering, at the device level, from solar particle events (SPE) and other radiation that may induce both single event upsets (SEUs) and longer-lasting "latch-ups" in circuits. Such devices have been in use for a number of years; however, a new requirement for SPS is that these systems also be affordable in mass production.

High- Temperature/Efficiency Electronic Materials. Throughout the primary array (as described in Chapter 5), more efficient electronics need to be fabricated from materials that can operate at higher temperatures.

Space-Based WiFi / Wireless Communications Networks. Wireless networks are well-known in terrestrial applications – they are deployed in innumerable homes and businesses across North America, Europe, and Asia. However, they are not yet used in space applications; this is a requirement for SPS-ALPHA.

High-Efficiency / Low Mass Solar Cells / Arrays. Existing space-qualified solar PV cells could certainly be used during the early stages of SPS-ALPHA development (flight demonstrations and early smaller-scale prototypes). However, more efficient PV cells with lower mass are required for economical SPS.

High-Efficiency / Low-Mass Retro-directive WPT with High-Efficiency Amplifiers. The best current solid-state amplifiers can operate with an efficiency of about seventy percent (70%) in the conversion of electricity into microwaves at one of the possible frequencies (2.45 GHz) that could be used for SPS wireless power transmission. This is high enough to implement SPS-ALPHA even at large scale; however, higher efficiency devices (e.g., 80% or more) would significantly improve the economic performance of the system.

Low Mass / Moderate Temperature Thermal Management. It is vital that waste heat resulting from less than perfect electronic device efficiency be rejected from the platform as effectively as possible. (In desktop computers, small electric fans accomplish this task by drawing cool air over the hot circuit boards; they also expel the warmed air from the computer.) The amount of heat to be removed will depend directly on the device efficiencies; however, the higher the allowable operating temperature of those devices, the more heat may be rejected.[6]

Modular / Reconfigurable Power Management & Distribution. Although power management and distribution (PMAD) for the baseline SPS-ALPHA architecture is entirely local, it would be highly useful if PMAD among neighboring modules in the transmitter array (see Chapter 5) could be reconfigured as needed to compensate for local component failures.

High-Efficiency / Moderate-Thrust Electric Propulsion. As has already been discussed, electric propulsion with good efficiency and thrust is essential both for the SPS-ALPHA platform and for the LEO-to-GEO transportation systems that will support it. (In my view, it is likely that a Hall Effect Thruster solution will be best; this was assumed in the recent NIAC Phase 1 study project.)

Highly Autonomous Systems and/or Reconfigurable Avionics. Achieving autonomy at the platform level will depend directly on highly autonomous and reconfigurable avionics modules – perhaps at the circuit level, but certainly at the "box" level and above.

Autonomous Robotics / Manipulators (in a Structured Environment). As discussed previously, SPS-ALPHA is fundamentally based on the idea of using terrestrially common, structured environment robotics in space. The optimal specific manipulators and interfaces must be defined, however, perhaps during the course of related technology R&D and demonstrations.

Autonomous Guidance, Navigation and Control (GN&C). The affordable delivery of literally hundreds of payloads from LEO to GEO will depend upon autonomous GN&C, including key technologies such as autonomous rendezvous and docking (AR&D). As in the case of the item above, optimal manipulators and interfaces are still to be defined.

Integrated TRRA for the SPS-ALPHA Roadmap / DRMs

In Chapter 15, a preliminary roadmap will be sketched for the development and deployment of SPS-ALPHA. That strategic programmatic approach will be framed around the series of focused, increasingly capable "Design Reference Missions" (DRMs) that were introduced in Chapter 10. In addition to representing a major advance in capability, each of these is also a potential milestone for interim space mission applications and early terrestrial energy markets.

In turn, accomplishing the objectives of each DRM will demand the same functionality (e.g., solar power generation), but with increasingly capable specific technologies. Each Module/Technology intersection identified above should be assessed for each of the five (5) DRMs, and each specific case examined by the study. In other words, DRM-1 can be accomplished with commercially available space-qualified solar arrays. However, achieving the macroeconomic objectives of DRM-5 will only be possible with significant improvements beyond commercial off-the-shelf (COTS) subsystems and technologies.

Developing a detailed TRRA for all of the technology requirements identified in Table 14-2, and for all of the DRMs and cases, was far beyond the scope of the Phase 1 NIAC project. For each of the five design reference missions and the sensitivity studies that have been performed, a host of highly specific technology choices were made to perform the project's systems analysis studies.

As a starting point, the following two sub-sections provide preliminary technology readiness and risk assessments for a handful of the most important technologies for two of the primary DRMs: DRM-2 (the initial integrated LEO orbital demonstration) and DRM-5 (the moderately advanced technology GEO full-scale solar power satellite).

TRRA for DRM-2

At a power level of about 200 kW and with deployment in LEO, DRM-2 is a major spacecraft; however, in the context of the major step yet to come – SPS-ALPHA DRM-3 (to be deployed in GEO) – , it is only a systems-level technology flight demonstration (TFD). Chapter 10 provides a summary description of SPS-ALPHA DRM-2 which would include deployment over several launches using robotic in-space assembly and construction. Table 14-3 presents the results of a high-level summary of this TRRA, including key technology areas and functional requirements.

Based on the values for the several R&D management metrics, Figure 14-3 presents the integrated Technology Risk Matrix for DRM-2 as developed using the methodology described above.

Table 14-3 Preliminary Technology Readiness and Risk Assessment for DRM-2

INDEX	TECHNOLOGY AREA	Goal TRL	Current TRL	ΔTRL	TNV	R&D³	NOTES**
2-1	Low-Mass / High-Strength Structural Materials / Systems	6	5	1	5	1	Conventional Materials acceptable (e.g., Aluminum)
2-2	Low-Mass / High-Reflectivity Thin-Film Reflectors	6	5	1	5	1	Current SOA may be acceptable (e.g., DLR solar sail)
2-3	Robust / Highly-Reliable Mechanisms / Actuators (& related Tribology)	6	5	1	5	1	ISS-type mechanisms may be acceptable
2-4	High-Aspect Ratio / High-Strength / Low-Mass Deployable Structural Systems	6	5	1	5	1	"*Astromast*-" - type structural systems may be acceptable
2-5	Radiation / SEU /Latch-Up Tolerant Electronic Devices	6	5	1	3	1	LEO operations only; no strong requirement
2-6	High- Temperature and Efficiency Electronic Devices / Materials	6	3	3	3	1	Low-power operations only; no strong requirement
2-7	Space-Based WiFi / Wireless Communications Networks	6	4	2	5	2	Adaptation of ground-systems as a starting point
2-8	High-Efficiency / Low Mass PV Cells and Solar Arrays	6	5	1	3	1	Conventional space-qualified solar arrays acceptable
2-9	High-Efficiency / Low-Mass Retro-directive WPT with High-Efficiency Amplifiers	6	4	2	5	2	Off-the-shelf devices acceptable; low power array
2-10	Low-Mass / Moderate Temperature Thermal Management	6	4	2	2	2	Minimal Thermal Management requirements
2-11	Modular Reconfigurable Power Management & Distribution	6	4	2	2	1	Minimal PMAD; no transfer among modules
2-12	High-Efficiency / Moderate-Thrust Electric Propulsion	6	4	2	1	1	Operational / Demo Systems

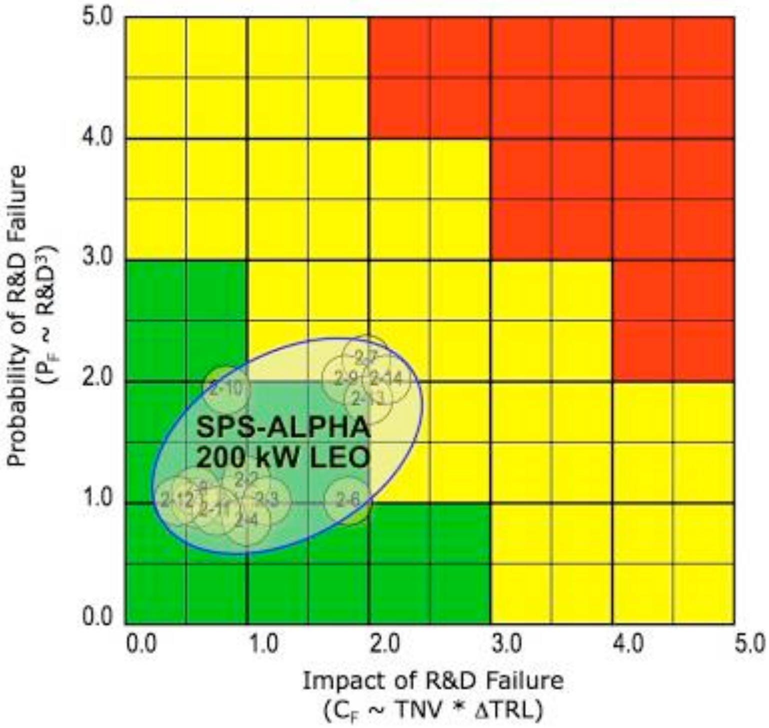
Table 14-3 Preliminary Technology Readiness and Risk Assessment for DRM-2

INDEX	TECHNOLOGY AREA	Goal TRL	Current TRL	∆TRL	TNV	R&D^3	NOTES**
2-13	Highly-Autonomous Systems / Reconfigurable Avionics	6	4	2	5	2	Operational / Demo Systems
2-14	Autonomous Robotics / Manipulators (Structured Environ.)	6	4	2	5	2	Operational / Demo Systems
2-15	Autonomous Guidance, Navigation and Control (GN&C)	6	3	3	5	2	Operational / Demo Systems

*Note: The timing for achieving TRL 6 at the end of Phase B for a DRM-2 Flight project would be approximately 7 years from 01 April 2013.

**Note: Major functional areas for DRM-2 (e.g., structural systems & materials) would include both more mature operational technologies, and more advanced technology options for preliminary testing.

Figure 14-3 Integrated Risk Matrix for DRM-2



As expected, the technologies for DRM-2 – although not yet tailored or matured for this specific space mission application – are nonetheless available in the laboratory or are in use for other applications; as a result, they were judged to be relatively low risk.

TRRA for DRM-5

DRM-5 represents a mature, recurring version of the SPS-ALPHA concept, capable of delivering 2 GW to terrestrial markets and requiring the successful development and maturation of a number of new technologies to succeed. Chapter 10 provided a summary description of the SPS-ALPHA DRM-5 case. Table 14-4 below presents the results a high-level summary of the initial TRRA for this case, including only key technology areas and functional topics. Based on those assessment results, Figure 14-4 presents the integrated TRRA risk matrix for DRM-5, developed using the methodology described above.

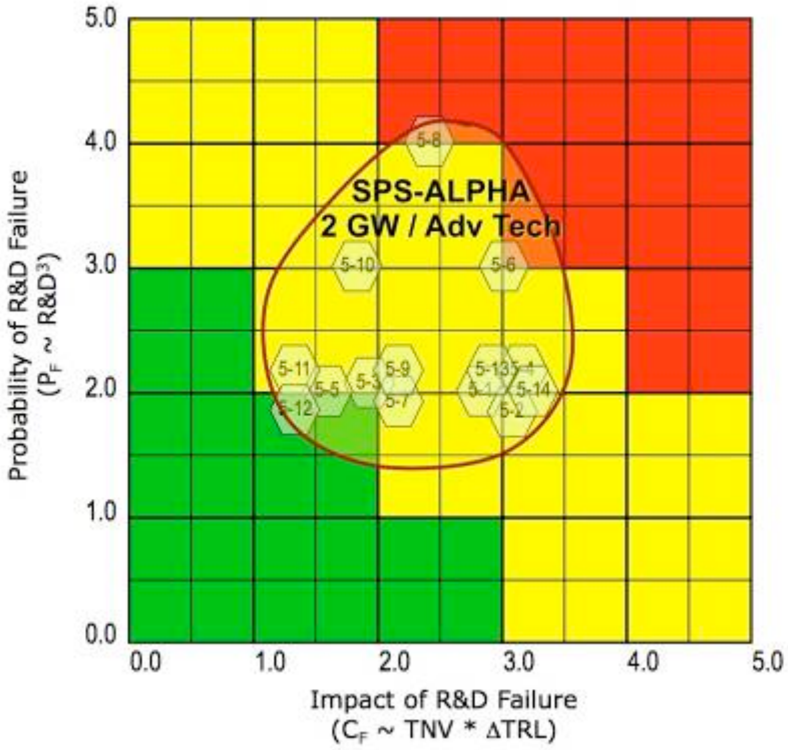
Table 14-4 Preliminary Technology Readiness and Risk Assessment for DRM-5

INDEX	TECHNOLOGY AREA	Goal TRL	Current TRL	ΔTRL	TNV	R&D^3	NOTES
5-1	Low-Mass / High-Strength Structural Materials / Systems	6	3	3	5	2	Must have advanced Materials (e.g., Composites)
5-2	Low-Mass / High-Reflectivity Thin-Film Reflectors	6	3	3	5	2	Need large/flat reflectors
5-3	Robust / Highly-Reliable Mechanisms / Actuators (& related Tribology)	6	4	2	5	2	Need mass-producible mechanisms / long-lived ops
5-4	High-Aspect Ratio / High-Strength / Low-Mass Deployable Beams	6	3	3	5	2	Need low-mass / reliable structural systems
5-5	Radiation / SEU /Latch-Up Tolerant Electronic Devices	6	4	2	4	2	Robust / GEO operations req'd; repair option
5-6	High-Temperature and Efficiency Electronic Devices / Materials	6	3	3	5	3	High-temperature device environment required
5-7	Space-Based WiFi / Wireless Communications Networks	6	4	2	5	2	Need reliable / secure large space-based networks
5-8	High-Efficiency / Low Mass Solar Cells / Arrays	6	3	3	4	4	Need high-efficiency / low mass arrays
5-9	High-Efficiency / Low-Mass Retro-directive WPT w/ High-Efficiency Amplifiers	6	4	2	5	2	Low mass by unit area, mass-producible transmitter array
5-10	Low-Mass / Moderate Temperature Thermal Management	6	3	3	2	2	Must have low-mass / moderate temp thermal
5-11	Modular Reconfigurable Power Management & Distribution	6	3	3	3	3	Local PMAD requires low mass; inter-module option
5-12	High-Efficiency / Moderate-Thrust Electric Propulsion	6	4	2	3	2	Long-lived / fine-pointing thruster
5-13	Highly-Autonomous Systems / Reconfigurable Avionics	6	3	3	5	2	Critical requirement
5-14	Autonomous Robotics / Manip-	6	3	3	5	2	Critical requirement

Table 14-4 Preliminary Technology Readiness and Risk Assessment for DRM-5

INDEX	TECHNOLOGY AREA	Goal TRL	Current TRL	ΔTRL	TNV	R&D3	NOTES
	ulators (Structured Environment)						
5-15	Autonomous Guidance, Navigation and Control (GN&C)	6	3	3	5	2	Critical requirement
	*Note: The timing for achieving TRL 6 at the end of Phase B for the DRM-5 Flight project would be approximately 25 years from 01 May 2013.						

Figure 14-4 Integrated Risk Matrix for DRM-5

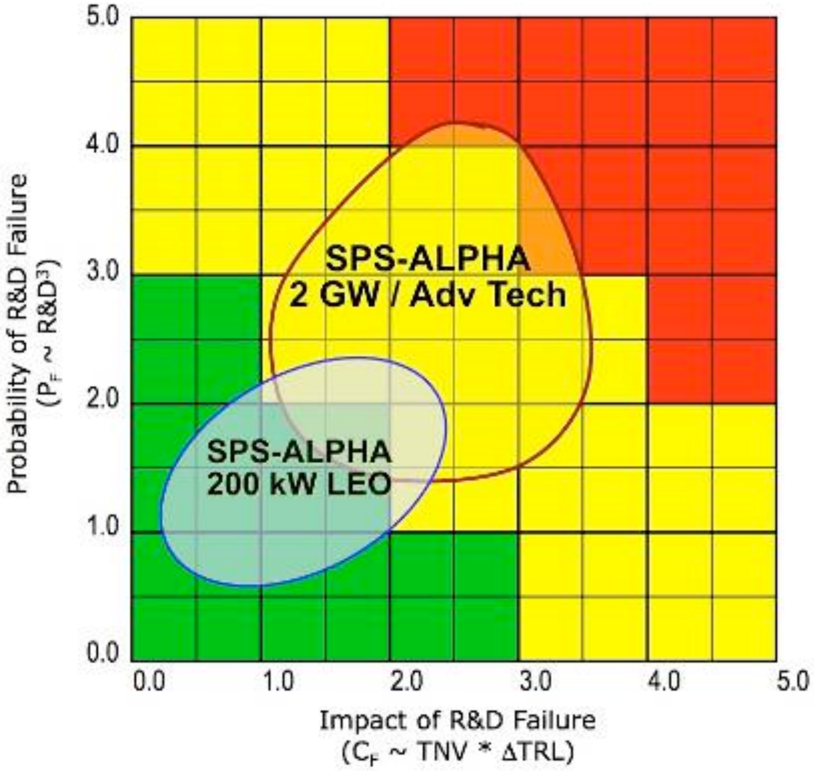


Closing Observations

A critical step in developing any new system is verification that the needed technologies are ready for systems development to begin – and that those technologies can meet the performance and cost requirements of the mission. The first steps in the development of SPS-ALPHA will require the application of diverse existing technologies in novel systems with new and distinct requirements. However, the latter stages (e.g., DRM-3 and later) will require both novel systems and new technologies. Fortunately, the systems-level innovations may be validated during the early design reference missions.

As a result, the TRLs tend to be relatively low, but the expected R&D^3 relatively good. The two DRMs chosen for detailed assessment span the SPS-ALPHA roadmap, ranging from an early (but substantial) demonstration to a mature commercially-feasible SPS with advanced technologies. As shown in Figure 14-5, the technologies required to accomplish DRM-2 are more mature and lower risk than those needed for DRM-5.

Figure 14-5 Integrated Risk Matrix for DRM-2 vs DRM-5



The upshot of this Chapter is three-fold. As we found in past assessments (albeit for other systems concepts), SPS-ALPHA appears to be doable without any technological breakthroughs. However, advances in several key components are needed to reach the goal of power for markets on Earth at costs of less than 10¢ per kilowatt-hour. Fortunately, the risks associated with the DRM-5 technologies needed in the mid-to-far term – even with the more advanced technology choices – appear achievable.

How then to best advance those technologies? The SPS-ALPHA roadmap presented in the next Chapter – which involves several rounds of innovation and demonstrations over more than a decade – represents a tractable and affordable approach to mature the needed technologies and mitigate the issues we've identified.

[14-1] This management "best practice" is called "knowledge-based decision making," or "knowledge-based assessment of technology maturity." It has been the topic of numerous evaluations of government programs by the US General Accountability Office (GAO). See, for example: GAO, "Best Practices: Better Management of Technology Development Can Improve Weapon System Outcomes," (General Accountability Office; Washington, DC). July 1999.

[14-2] Unlike SPS-ALPHA and other sandwich type SPS concepts, SSP architectures that separate solar power generation and wireless power transmission systems (e.g., the 1979 SPS Reference System, the ISC, etc.) also require significant improvements in the systems that connect the two. These are discussed in the next section.

[14-3] See: http://www.upenn.edu/pennnews/current/2011-03-03/research/have-you-seen-videos-those-amazing-flying-machines

[14-4] See: Mankins, J.C., "Technology Readiness Levels" (a White Paper; NASA Headquarters, Washington D.C.). 1995.

[14-5] See: Mankins, J.C., "Research and Development (R&D3) Degree of Difficulty" (a White Paper; NASA Headquarters, Washington D.C. 1998.

[14-6] This is a good time to reiterate a point made previously; namely, that the technologies needed for different Solar Power Satellite concepts vary greatly. For example, in the case of SPS-ALPHA, only relatively low temperature thermal management is needed. In the case of other options, such as modular laser WPT concepts, high-temperature thermal management would be required.

Chapter 15

A Path Forward for Space Solar Power

The SPS-ALPHA Roadmap

> *"Whatever course you decide upon, there is always someone to tell you that you are wrong. There are always difficulties arising which tempt you to believe that your critics are right. To map out a course of action and follow it to an end requires courage."*
>
> *Ralph Waldo Emerson (1803-1882)*
> *American Poet, Lecturer and Essayist*

Introduction

What exactly *is* a roadmap?

As commonly understood, a roadmap is a metaphor derived from actual maps depicting real roads. Different organizations and individuals use the term "roadmap" to refer to a variety of different long-range planning documents. In essence, a roadmap is a plan for action, usually graphically constructed. The best are designed to be strategic such that the roadmap allows for tactical changes in course (detours, if you will) if circumstances demand, without sacrificing overarching objectives (the destination).

The roadmap for SPS-ALPHA presented here is just such a plan for action: detailed enough to guide decisions, but flexible enough to allow for changes in course if necessary. Most importantly, the roadmap is programmatically tractable: it can be accomplished with a feasible amount of funding and in a reasonable length of time. Before reviewing the SPS-ALPHA roadmap, let's take a moment and review two important past SPS roadmaps: the 1980 roadmap developed by the US Department of Energy and NASA during the late 1970s SPS study, and that developed two decades later by NASA SSP Exploratory Research and Technology (SERT) program.

Past US Roadmaps for Solar Power Satellites

The two major roadmaps for Space Solar Power developed by the US government have been presented to the National Research Council – the first in 1980 and the second twenty years later in 2000. Each of these reflected program "norms" of the period from which they emerged and the perspectives of the individuals involved in their creation.[1]

The US Roadmap for SPS in 1980. In the late 1970s, there was strong interest in – and equally strong opposition to – the concept of the Solar Power Satellite. During those years several bills were introduced in the US Congress that would have established a major program to proceed with either a large-scale flight demonstration or the full-scale development of SPS. At the time, there were also cogent arguments made that the development and demonstration of SPS should be a longer-term strategic effort (analogous in retrospect to the now 60-year R&D program to prove the feasibility of fusion energy).[2] The latter were not successful; the Apollo Program model (discussed below) was too strong to be overcome for some, and others *may* have wished to see a massive, expensive proposal – which would be much easier to put to rest. At any event, the joint DOE-NASA program was required to identify both a baseline system design (the 1979 SPS Reference System), and a roadmap for its implementation – which it did. The results of numerous studies, the Reference System concept and the baseline program implementation planning were all presented to both the Congressional Office of Technology Assessment (OTA) and to an independent panel chartered by the National Academy of Sciences (NAS) National Research Council (NRC) circa 1980.[3]

The 1980 roadmap, not surprisingly, followed a program model that would have been quite familiar to the senior engineers who worked on the Apollo Program, which had ended less than a decade before. It involved a single stupendously grand project plan with several phases and an expected duration of approximately 20 years or so. It was to begin with a few years of background R&D and systems design, followed over several stages by development and deployment of (1) a large Two State to Orbit (TSTO) reusable launch vehicle (RLV) capable of carrying large payloads to orbit (10-times larger than those carried by the Space Shuttle); (2) orbital space station factories in LEO and GEO (to be 100-times larger that the International Space Station more than a decade later); (3) the SPS itself, a single system at about 51,000,000 kg delivering 5 GW to a station on Earth; and, (4) ground infrastructures (including the power receiver, mission control and communications systems, and launch and launch control). Each stage would have required about 4-6 years, and the annual budget would have increased from 10s of millions of dollars at first to more than 100s of billions of dollars annually (in 2013 dollars) within about ten years or so.

It should also have been no surprise that this plan was projected to cost more than $300 to $1,000 billion to first power, and total perhaps as much as $10,000 billion for a constellation of

60 SPS platforms (both in 2013 dollars). Both the OTA and the NRC panel doubted strongly the economic feasibility of SPS and found the 1980 Solar Power Satellite roadmap as presented to be problematic, even though the idea of SPS was generally judged to be technically feasible.[4]

The NASA Roadmap for SPS in 2000.[5] The SSP technologies used and SPS architectural approach emerging from the NASA Fresh Look Study (1995-1997) and the SERT Program (1999-2000) were radically different from those of the 1970s studies. The roadmap for R&D implementation was similarly different: the technologies involved considerable robotics and solid-state electronics, and the architectures were more modular (e.g., SunTower, Integrated Symmetrical Concentrator, etc.).[6] The 2000 roadmap produced was not a single project but instead involved a series of related but distinct efforts.

As presented to an NRC review panel in 2000, the roadmap was organized into a series of focused projects, each of which would nominally last for 5 years, and each of which would begin with the technological heritage of the prior effort. The total duration of the program before reaching a full-scale (GW-class) SPS would have been some 25 years, and each stage would have resulted in a major flight demonstration. No single piece of an eventual SPS would have been larger than 20 MT – small enough to launch on a relatively small ETO vehicle – although the total masses of full size SPS were quite similar to those of the 1979 SPS Reference System. Ground infrastructures were, of course, still required (including the power receiver, mission control and communications systems, and launch and launch control), but with a much greater degree of presumed autonomous in platform operations.

The 1990s SPS concepts were only partially modular; they also involved key integrated features – such as the power backbone in the case of the SunTower concept or the gimbaled interface of the Abacus-Reflector SPS. As a result, the development and demonstration of these integrated features at higher and higher power levels (e.g., first at 100 kW, then at 1 MW, then at 10 MW, and so on) was a defining characteristic of each demonstration. Moreover, each demonstration was proposed with secondary applications in mind; for example, the 10 MW SunTower SPS demonstration might also have been adapted for use as an interplanetary solar electric propulsion (SEP) vehicle. Another important aspect of the 2000 SPS Roadmap was that it did not require huge new infrastructures (such as in-space factories), and those infrastructures it did need did not have to be developed concurrently with the early years of SPS development.

For example, a smaller RLV was needed (perhaps 20 MT payload), but its development could be postponed until after the first 10-15 years of SSP R&D had been successful.

No firm estimate was provided beyond the first 5 years; however, the 2000 SSP roadmap was projected to cost no more than roughly $30-$40 billion to the first full-scale SPS: still a great deal of money, but averaging less than $2 billion per year (comparable to the Space Shuttle program) it was far less expensive than the $300 billion-$1,000 billion required for the 1980 plan.[7] The NRC review panel was not yet sanguine about the economic feasibility of Solar Power Satellites, but found the new roadmap for Space Solar Power to be both viable and highly beneficial to other space program efforts. Despite improvements in project costs and assessments confirming technical feasibility, the 2000 roadmap failed just as had the 1980 plan: the US Government did not adopt the goal of Space Solar Power.[8]

In summary, from 1980 to 2000, US planning for SPS development evolved from a large, Apollo-like single project toward a program strategy that resembled what is known today is "iterative development" or at one time as "spiral development" used by DOD – both terms typically associated with software-related development.[9] This evolution set the stage for the Space Solar Power roadmap that follows.

The SPS-ALPHA Roadmap

As we've already discussed, the hyper-modular architectural approach to large, high-power space systems embodied by SPS-ALPHA appears to be technically feasible. Moreover, the technologies, systems, and infrastructures involved would – if developed – be broadly important for future space applications. A deliverable from the 2011-2012 NIAC Phase 1 project was a preliminary roadmap that presented a credible path forward for SPS-ALPHA and the hyper-modular architectural approach. Figure 15-1 presents this preliminary systems and technology roadmap for development of the SPS-ALPHA concept and various spin-off applications.

Roadmap Ground Rules. Several ground rules were imposed in framing the NIAC Phase 1 SPS-ALPHA Roadmap.[10] First, the detailed milestones included in the roadmap could not depend on the specific budgets invested by government or commercial organizations. Second, the roadmap produced could not be schedule- and/or calendar-specific (since both of these are dependent on budgets). Rather, the roadmap was to be strategic in character, providing a coherent and flexible framework for a wide range of prospective government, industry, and academic institution activities to advance space solar power. However, the roadmap could indicate roughly what could be accomplished in terms of schedule and technology maturity, depending on budgets and programs.

The resulting roadmap recognizes that the business model by which SPS-ALPHA may be developed is by no means fixed. Development options include: (1) a major government project (including both national and international components), (2) public / private partnerships (potentially involving multiple governments), and (3) privately-funded ventures. Novel approaches such as "Prize Challenges" might also play a role. The roadmap is entirely flexible in terms of which of these development mechanisms might ultimately be employed – or even (which is most likely) if different aspects of the roadmap follow different development organizational approaches. (For example, the SPS might be developed through a public / private partnership, while the launch system(s) used might be either private or government provided.) The key elements of this roadmap include:

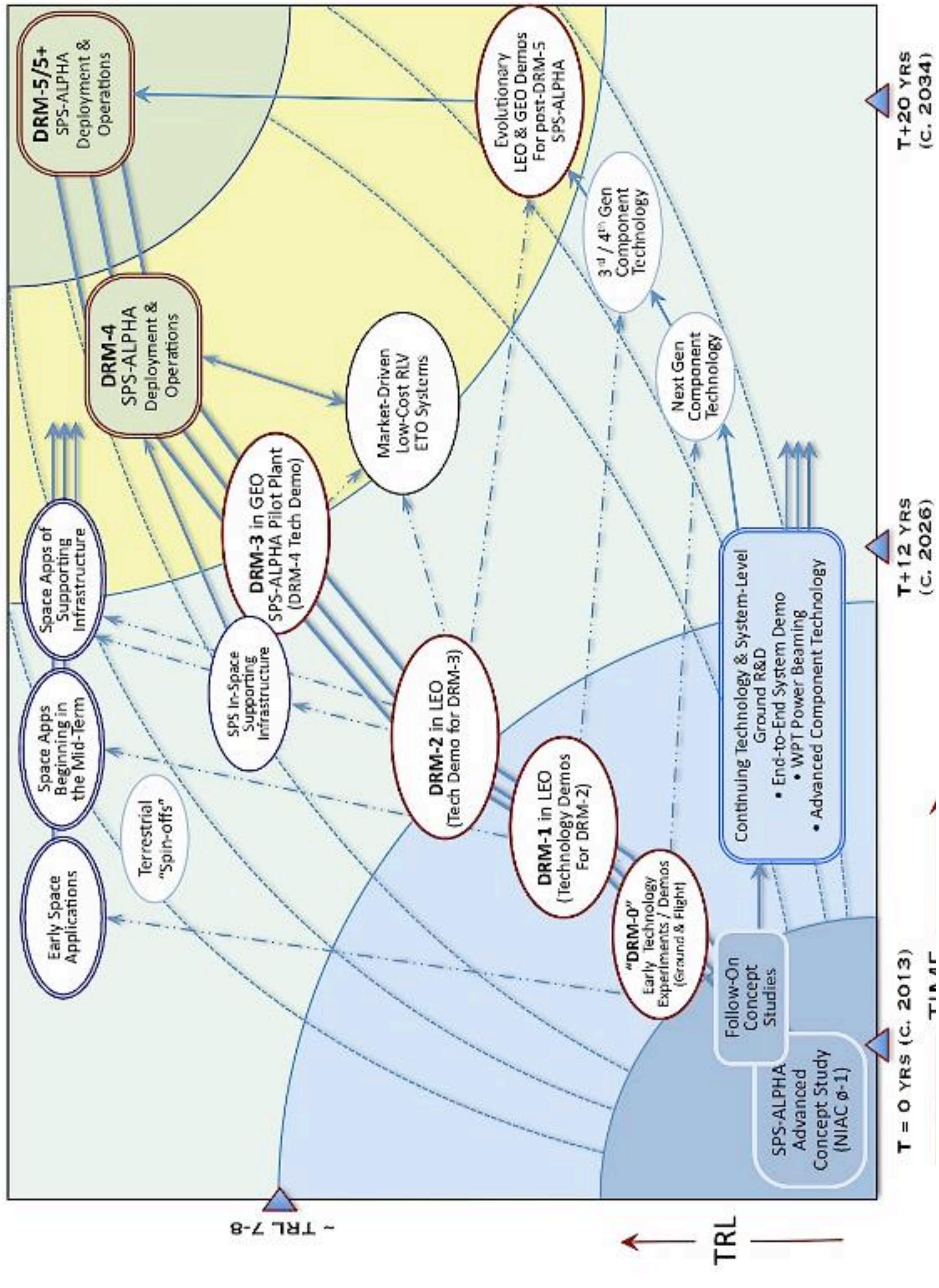
- Early advanced concepts study projects;
- Continuing SPS-ALPHA and supporting infrastructure concept studies, and related advanced technology research projects;
- Ongoing focused technology research and development to realize continued improvements in the efficiency, operating temperature, and mass of key devices (and thereby enable evolutionary commercial viability for large-scale space solar power in terrestrial markets);
- A regular series of systems-level technology demonstrations, targeting Design Reference Missions (DRMs) that we discussed earlier with strong nearer-term space applications and culminating in a large-scale pilot plant SPS-ALPHA demonstration in GEO; and
- Orchestrated development of supporting infrastructures and derived space applications

As we discussed in Chapter 10, a strategic set of individual Design Reference Missions have been constructed that represent candidate milestones in the strategic roadmap for SPS-ALPHA presented here. In developing the business case for SPS-ALPHA (Chapters 11-13), the addition of a DRM-0 proved useful.) The full set of DRMs incorporated in the roadmap includes:

- DRM-0: a collection of ground tests (and perhaps in-space technology flight experiments) representing the earliest possible integrated test bed for SPS-ALPHA modules and technologies.

- DRM-1: an initial SPS-APHA technology flight experiment (TFE) / technology flight demonstration (TFD) in low Earth orbit (LEO) at a small scale (see **Figure 15-5).**
- DRM-2: a second SPS-APHA demonstration in LEO at a moderate scale, incorporating operational technologies such as ISAAC. (see **Figure 15-1**). Both DRM-1 and DRM-2 will test technologies intended for incorporation into DRM-3.
- DRM-3: the first major SPS-APHA demonstration in geostationary Earth orbit (GEO) at a large scale, but not yet full-scale (see **Figure 15-1**). DRM-3 will demonstrate technologies for incorporation into DRM-4.

Figure 15-1 The SPS-ALPHA Systems-Technology Roadmap



> DRM-4: an initial operational SPS-APHA in GEO at up to 1 GW scale (see below). DRM-4 (and later versions) will provide opportunities to test new technologies intended for incorporation into later versions of SPS-ALPHA.
>
> DRM-5 (and later): the first full-scale operational SPS-ALPHA demonstration in GEO at up to 2 GW scale. This platform (and subsequent generations) would provide a context for late increasingly advanced technology validation.

A central tenet of this roadmap is that, because the SPS-ALPHA architecture represents a radical systems level departure from past space systems practices, a series of major technology flight demonstrations will be essential to establish confidence in this novel approach. Although preliminary estimates were discussed at several points in the preceding Chapters, it is important to recall that the ultimate costs and prices of energy delivered from SSP systems have not yet been established. However, the economics of SPS-ALPHA will clearly depend on both the engineering of the SPS platform and its supporting systems and the markets that such systems seek to serve. As a result, this roadmap for SPS-ALPHA provides for self-evident technical accomplishments and for periodic and timely progress in the development of energy markets and commercially viable applications of key SSP technologies and systems.

The following paragraphs sketch the major components of this roadmap, including additional details concerning the DRMs.

Descriptions of Major Roadmap Components

Early & Continuing Technology R&D

Although no fundamental advances are required (i.e., no “breakthroughs” in science) to realize SPS-ALPHA, given the broad scope of systems and infrastructure that SPS-ALPHA represents, a similarly wide range of studies and basic technology research involving diverse areas are needed. Moreover, in order to realize the longer-term potential of the SPS-ALPHA architecture to deliver power to terrestrial markets at commercially competitive prices, significant improvements will be required over component technologies available in space systems at present (c. 2013). In addition, considerable research, prototyping and broadly-based coordination will be needed in order to finalize the full range of system architecture details involved, including module-to-module interfaces and interactions. As a result, there is a need for early and continuing technology research and development activities as a part of the roadmap for SPS-ALPHA; these include the following topics:

Systems Concept Studies. Beginning with the 2011-2012 NASA-supported NIAC Phase 1 study project, a program of increasing fidelity modeling, simulation, and analysis of the SPS-ALPHA design reference missions, technologies, and supporting systems is needed. The ideal result from near-term system studies would be to reach general agreement regarding one or two basic architectures and system designs into which ongoing component-level improvements were to be later incorporated. The identification of such a higher-level framework for SSP R&D should be a key goal for systems analysis and design studies. (The sensitivity study results we discussed in Chapter 10 are an example of this type of analysis.)

Technology & Component-Level R&D. This R&D should address development and prototyping of key components and subsystems. As discussed in Chapter 14, such relevant areas for component technology R&D include: (1) FET amplifiers (for sandwich type concepts); (2) thermal management systems; (3) modular PMAD systems, and others. For example, experiments have been performed in recent years that have validated several of the novel technologies (e.g., retro-directive phase control for wireless power transmission, WPT) that are needed to enable the hyper-modular = architectural approach to SSP.[11] Development and demonstration of prototype SPS-ALPHA modules is an important aspect of this R&D. These prototypes enable refinement of interface designs, and feed into the DRMs over time.

Sub-System and Component Level Technology Flight Experiments. In a number of cases, only the space environment can allow the necessary experiments and tests to be conducted to mature a particular technology. In the case of space solar power R&D, there are a number of possible technology flight experiments (TFEs) that may be needed to verify component and system performance, and to validate systems integration design choices. (Systems level technology flight demonstrations are discussed below.) Some of the most important prospective TFEs include:

- Wireless Power Transmission Experiments;
- Large Space Structures and In-Space Assembly Experiments; and
- SPS Platform Component Experiments.

A topic of particular importance for future TFEs is that of wireless power transmission. Although many of the fundamental aspects of the engineering of WPT can be developed and demonstrated through ground-based and airborne technology experiments (see the example described above), there are a range of specific TFE options that will require the use of the space environment. Tests of wireless power transmission in space could include:

- Ground-to-Space WPT Tests
- Space-to-space WPT Tests
- Space-to-Ground WPT Tests (from LEO)
- Space-to-Ground WPT tests (from GEO)

Such TFEs result in validation of technology maturity in the range of TRL 4 to 5 (see Chapter 14). In addition, these experiments can contribute to a better understanding of the interactions between the WPT transmission and the environment – in space and in the atmosphere. Tests of microwave power transmission at various power levels from LEO to the ground, for example, appear very useful in further evaluating the interactions of the WPT beam with the ionosphere.

During the past 40 years, a variety of lower TRL SPS-relevant technology flight experiments and ground technology demonstrations have been performed – particularly in the field of wireless power transmission. The earliest of these involved specific component technologies that may no longer be fully relevant to eventual SPS realization. Other components (particularly involving Rectennas) have been successfully demonstrated over the years. A variety of additional technology developments / demonstrations are also ongoing. These include development of microwave and laser WPT ground tests by USEF / JAXA in Japan, development of a sandwich panel test article by the U.S. Naval Research Laboratory (NRL), and laser power transmission studies at EADS Astrium in Europe.

Another important area for technology development leading to TFEs is that of large space structures and in-space assembly and construction (ISAAC). The deployment and/or assembly of very large space structures in a zero gravity space environment are two of the most obvious areas in which future technology flight experiments could prove invaluable. In recent years, one concept that has been discussed is that of using a large lightweight mesh as a scaffold for the in-space assembly of the transmitter/PV array of an SPS of the sandwich type. Initial flight experiments have been conducted using a sounding rocket to launch a test system (using a simple rotating mesh deployment scheme).[12] Other deployment approaches, such as inflatable structures to which the mesh might be attached also appear promising. A key requirement in this case will be to assure that structural concepts and in-space assembly technologies (e.g., robotics) are researched and tested in concert. Large space structures and/or in-space assembly TFEs would result in validation of technology readiness levels in the range of TRL 4 to 5.

Next Generation Component Technologies. By its nature, SPS-ALPHA will accommodate ongoing evolutionary developments in key components and in several modules. For example, after DRM-3, a range of SPS platform component technology advancements will be needed to implement DRM-4 (the first full-scale GEO SPS). These would be good candidates for technology flight experiments (TFEs). The objectives of such tests would include (a) verifying the performance of key components (e.g., solar cells, PMAD system elements, electronics, communications systems elements) in the space environment; (b) verification of key mechanisms, actuators, and related tribology for key SPS components; and (c) lifetime testing and related servicing and maintenance demonstrations for the full range of prospective SPS components and subsystems. Such TFEs would result in validation of technology maturity in the range of TRL 4 to 5. The same program strategy will "play out" for the first DRM-5 and for all subsequent versions – whether for Solar Power Satellites or for space missions applications. Each generation of flight system will host technology experiments and demonstrations for the next.

DRM-0: Early SPS-ALPHA Testbed

As soon as are there are more than two modules of a given type, testing of multiple modules in integrated configurations must begin. These "DRM-0" experiments could be realized within the next 2-3 years – first on the ground and then (perhaps) in space. Another programmatic approach would be to stage this DRM as an attached payload on the ISS.

DRM-1: Initial SPS-ALPHA LEO TFD

During the next 4-6 years (with necessary funding), an initial SPS-ALPHA technology flight demonstration could be staged in a low Earth orbit (LEO), incorporating technology flight experiments involving various new space applications of technologies now in the laboratory. This mission, labeled here as "DRM-1," would almost certainly involve a single launch and a free-flying mission. Staging this mission from the ISS, perhaps with astronaut assistance in the assembly of the primary array and HexFrame structures, is an option.

DRM-2: Moderate-scale SPS-ALPHA LEO TFD

Following DRM-1, within the next 6-9 years, a fully functional SPS-ALPHA TFD could be staged in LEO. This mission, labeled here as "DRM-2," could incorporate the technologies tested in DRM-1 as baseline systems as well as accommodating TFEs of more advanced component technologies. DRM-2 would involve more than a single launch, and would demonstrate in-space assembly and construction operations using prototype (TRL 7) versions of the MARE arms and related technologies. A prototype of the propulsion and attitude control assembly (PACA), described in Chapter 5, would be tested at this stage.

DRM-3: SPS-ALPHA Pilot Plant in GEO

In cases where the overall R&D and conceptual "riskiness" of a new space system is judged to be low, full-scale system development may proceed once individual technologies are validated at TRL 5 (or TRL 6 at most). However, in the case of a novel and ambitious new system such as SPS-ALPHA, a higher level of technology demonstration will almost certainly be required. There are two interrelated but distinct aspects of DRM-3, the mid-point in the proposed roadmap for SSP: (1) development, deployment, and operation of both SPS pilot plants (perhaps at sub-scale, but capable of being scaled up), and (2) development of space applications of SSP technologies and systems at the subscale.

In order to qualify as a true "pilot plant" rather than a technology experiment or demonstration, it is crucial for the system being demonstrated to be at a sufficient scale so as to allow testing and validation of essentially all aspects of the end-to-end challenges of building, launching, deploying, assembling, and operating a solar power satellite. A typical rule of thumb might be that an SPS Pilot Plant should be capable of generating a wireless power transmission approximately 10% of the power level of a full-scale SPS using the same suite of technologies, but certainly not less than 1% of that power level. An SPS pilot plant might also be used to deliver power operationally (albeit at lower power levels) to large-scale receivers on Earth positioned in locations that are relevant to, if not the same as, anticipated later market locations.

Also as part of the DRM-3 project, critical aspects of the in-space infrastructure – including affordable in-space transportation (AIST), as we discussed in Chapter 7 – would be demonstrated. The successful completion of such demonstrations would open up the possibility of tremendous new space mission applications, ranging from very large GEO communications platforms to low-cost, large-scale transportation across the inner Solar System. (These were touched on in Chapter 11.)

The design and development of DRM-3, an SPS pilot plant, would itself be a tremendous undertaking. The purpose of which would be to validate system designs and key technologies before committing to full SPS development. In fact, the SPS concept is sufficiently transformational and entails enough technical uncertainties at the systems level such that major in-space demonstrations will be necessary to establish technical feasibility, engineering characteristics, and economical viability before any organization is likely to proceed with full-scale development.

DRM-4: First "Full-Scale" SPS-ALPHA Platform in GEO

The penultimate stage in the SPS-ALPHA roadmap is the development, deployment, and operation of the first full-scale SPS to deliver substantial energy to commercial markets, including baseload power markets. The strategic backbone of the roadmap presented here is a radical departure from the standard aerospace systems engineering process (which progresses from Pre-Phase A, to Phase A, to Phase B, and then to Phase C/D) for both the SPS platform and for key supporting systems and infrastructure.[13] The 1980 roadmap for SPS followed this management approach on a grand scale; the entire effort would be managed as a single, vast project. The roadmap for SPS-ALPHA is based on repeated cycles of rapid prototyping and demonstrations where each cycle follows the standard model, but – taken as a whole – it is radically different. Rather, it follows the evolutionary transformational approach seen in so many technologies in use today (including tablet computers, smart phones, the "internet of things," etc.).

A critical new capability that is enabling for DRM-4 and later versions of the SPS-ALPHA is that of reusable launch vehicles (RLVs) for Earth-to-orbit (ETO) transportation. As we discussed in Chapter 7, in the mid-term, only RLVs have the potential to accomplish the low-cost launch costs essential for delivering power at a competitive price to commercial markets on Earth. Such systems must be capable of launching both the platform modules and the systems and logistics necessary for the in-space transportation systems (deployed to accomplish DRM-3).

DRM-5 and Beyond: Subsequent SPS-ALPHA Platforms in GEO

The ultimate "destination" in the SPS-ALPHA strategic roadmap toward which all other components are directed is that of operational, large-scale Solar Power Satellites delivering commercially competitive energy to markets on Earth. DRM-5 is the designation for such SPS in the roadmap presented in Figure 15-1. Various details regarding this design reference mission were discussed in Chapter 10. The key parameters are: (1) power delivered is roughly 2 GW from a large platform based in GEO; and (2) the system involves continuous annual repair and maintenance (at a rate of about 3% per year of hardware being replaced), thus providing an ongoing opportunity to introduce new technologies and systems improvements.

The critical objective of DRM-5 is to deliver power at prices that are competitive in baseload markets. (Based on the systems analysis studies performed under this study, it appears that several technology enhancements will be critical to achieving this objective. The roadmap presented here provides the needed strategy of repeating cycles of innovation to accomplish this end.)

SPS In-Space Supporting Infrastructure

The earliest TFEs and TFDs in the roadmap will not require any new in-space infrastructure. However, as we have seen, accomplishing later demonstrations beyond LEO and on larger scale will demand new in-space capabilities. Detailed requirements for such future systems remain to be defined, but will almost certainly include infrastructure such as in-space refueling capabilities (for both the SPS-ALPHA platform and affordable in-space transportation systems), vehicle assembly, and maintenance systems, and others.

Terrestrial "Spin-Offs"

Early and continuing terrestrial market applications of SPS-ALPHA technologies will be one factor in judging the overall economic viability of the SPS-ALPHA concept. For example, we discussed in Chapter 11 the specific idea of a point-to-point WPT application to meet the power needs of niche markets. It is unclear at present how many of the "spin-offs" that could emerge from SPS-ALPHA related R&D will in fact prove to be "spin-ins."

Space Applications

As we've seen, an important aspect of SSP technology development – and the nearer-term economic viability of SPS – is that of finding interim milestones and applications for the technologies, components, and systems to be developed. This concept is in-line with the phrase "pay as you go" – i.e., the idea that SSP development should entail meaningful, and hopefully profitable, applications long before Solar Power Satellites begin delivering power to terrestrial markets. As we've discussed, there are a variety of prospective space systems applications for (1) SPS platform subsystems and systems; (2) in-space transportation systems; (3) in-space infrastructures; (4) ETO vehicles; and others. In particular, there are a variety of potential space applications of SPS-ALPHA technology that are consistent with the power levels that would typically characterize early demonstrations, up to early demonstrations, up to a "pilot plant" for a full scale operational SPS. (We discussed these in some detail in Chapter 11.)

Near-Term Space Applications. These include both commercial and government applications in novel Earth-orbiting spacecraft, such as larger aperture telecommunications satellites in low Earth orbit and higher orbits. These applications would involve the use of the key technologies and systems deriving from DRM-0 and DRM-1, but would still be limited in scale to a size that could be conveniently deployed on a single launcher with a conventional upper stage (where needed).

Mid-to-Far Term Space Applications. These include potential applications for ambitious future space missions and markets, such as lunar resources development, human Mars missions, and others. Whereas nearer-term applications would involve only the SPS-ALPHA platform, later mission and market opportunities would also involve the supporting infrastructure emerging from the SPS-ALPHA roadmap, including – as we mentioned above – affordable in-space transportation systems.

SPS Market-Driven Space Transportation Systems

A critical question for Space Solar Power is always that of space transportation, including Earth-to-orbit (ETO) transportation (vehicles and infrastructure) and in-space transportation. An important and relatively new idea in SSP planning[14]is that the development of fundamentally new, reusable launch vehicles (RLVs) for SSP can and should be deferred until after the successful completion of an SPS pilot plant in GEO. Technology maturation, hardware development, and system deployment for a very low-cost, highly reusable space transportation system will likely require an investment of some billions to perhaps tens of billions of dollars ($, US). If such RLVs are developed independently of SPS requirements, this is all to the good. However, if the SPS concept is the sole – or even a significant – market justification for such a development, then it is likely that the demonstration of a large-scale, SPS pilot plant will be required prior to any government and/or commercial commitment to fielding HRST systems or supporting infrastructure. This, at any rate, is the working assumption embodied in the SPS-ALPHA roadmap.

In-space systems and infrastructures that will support SPS deployment, assembly, servicing, etc. will be intimately related to the detailed designs and characteristics of the SPS platform, and to the design of support ETO systems. Such in-space systems will likely need to be developed and demonstrated in tandem with, if not prior to, the implementation of an SPS pilot plant demonstration. Such systems level in- space demonstrations would result in validation of technology readiness levels in the range of TRL 7 and higher.

Evolutionary LEO & GEO Demonstrations

As we've discussed, even after the successful completion of DRM-3 (the SPS-ALPHA pilot plant), there will be a need for continuing technology flight experiments and demonstrations involving evolutionary new technologies intended for future generations of the SPS-ALPHA platforms and supporting infrastructures. The roadmap assumes that these ongoing technology developments will be accommodated on a regular basis during the deployment and installation of replacement parts on existing SPS.

Scope of the Roadmap

The overall estimated economic scope (e.g., cost for development, etc.) presented (based on integrating the cost estimates from Chapter 10) suggests that the total scope of the roadmap described here would be on the order of $30B, over a period of time of about 25 years or more. This is substantial, but compares well to circa 1980 estimates of roughly $1,000B to accomplish the first SPS.

R&T Goals and Objectives

Across the various piece-parts of the roadmap, there are a number of research and technology development goals and objectives that must be pursued. Based on the results of the systems analysis performed as part of the NIAC Phase 1 study, goals and objectives for SSP and related technology R&D were established. These range from very high-level goals at the systems-technology level to more focused objectives at the component technology level. As we've seen, the high-level, critical SSP technology R&D goals and objectives may be expressed in terms of a handful of figures of merit:

- Specific Mass. For a Solar Power Satellite delivering commercial baseload power, the specific mass per unit power delivered on Earth should be roughly in the range of 1-5 kilograms per kilowatt delivered;[15]
- Installed Cost. For SPS, the installed cost (including all elements) should be in the range: $1,000-$3,000 per kilogram on orbit;[15] and,
- Lifetime. The expected lifetime of each kilogram of SPS platform mass should be in the range of 20-30 years or greater.

As has been discussed elsewhere, each of the above R&D goals comprises a variety of interrelated technical and economical objectives. The detailed quantitative formulation of the key goals and objectives (including for each system's and/or sub-system element's "threshold" and "goal" objectives) should be an objective of future end-to-end SPS systems analysis studies.

Closing Observations

In order to realize the benefits of Space Solar Power for space missions and markets and to establish the economic feasibility of SPS-ALPHA, a broad range of technical challenges and programmatic hurdles must be addressed. Given the highly modular nature of the concept and the incremental, initially modest investments required, it is possible that a single government or major company might surmount these challenges. However, it seems to me that timely success will more likely to result from cooperation in accomplishing R&D objectives among governments, among industry players, and among a broad range of government, corporate, and academic organizations.

A variety of tests and demonstrations of one key technology – wireless power transmission (WPT) – have been performed since the 1960s. However, many of these tests have involved component technologies that are not directly relevant to validating the economic viability of SSP.

Moreover, selected early demonstrations have been performed by various organizations almost as a means of "getting their feet wet" – i.e., in learning the basics of WPT and/or SPS. Unfortunately, the next steps in moving higher in the TRL scale require considerably greater funding (i.e., from the lower left to the upper right in the roadmap); these key steps have not yet been taken.

Timely communication of plans and results from SPS technology R&D activities is crucial to coordinated progress. The ongoing Space Power Symposium, organized annually under the auspices of the International Astronautical Federation (IAF), has served a highly useful role in this regard. Similarly, periodic conferences dedicated to SPS and WPT have been held over the past 20+ years in various countries (e.g., WPT 1995, SPS 2004, etc.); these have been highly useful in promoting international dialog and coordination of SSP efforts. In addition, following the completion of the 2008-2011 IAA assessment of SSP, the Academy formed a Global Space Solar Power Working Group, which seeks to coordinate relevant international activities.

This Chapter presented a preliminary roadmap for SPS-ALPHA, framed in strategic terms, for the potential exploration of this innovative concept. This roadmap is not highly specific; it does not prescribe a specific budget nor does it involve a specific schedule. However, it provides a framework for future SPS-related activities by indicating a logical sequence for various steps and the conceptual relationships among those steps. Moreover, it is the consensus of the IAA that significant progress could be made during the next 10-15 years – leading to a large, but sub-scale SPS pilot plant.

The roadmap to SPS-ALPHA is incremental, measurable, and affordable. Based on the hyper-modular architecture, it can be realized not only in tractable budget "chunks" but also in a doable length of time – not 100s of billions to trillions of dollars and decades, but millions of dollars (at first) to 10s of billions of dollars (later) and years. With this final piece of the puzzle in hand, the case for Space Solar Power may be summarized.

[15-1] The background for both of these roadmaps was discussed in Chapter 3.

[15-2] See: Grey, Jerry, et al; "Solar Power Satellite: A Plea for Rationality" (Science Magazine; Volume 203, page 709). 1979.

[15-3] See: Committee on Satellite Power Systems, "Electric Power from Space: A Critique of a Satellite Power System," (National Academy Press; Environmental Studies Board, Commission on Natural Resources, and the National Research Council; Washington, D.C.). 1981

[15-4] For reference, in 2013 dollars the initial cost to first power for the 1979 Reference would have been approximately $300 billion to $1,000 billion. The cost for deployment of the full constellation would have been about $3,000 to $4,000 billion.

[15-5] See: National Research Council, Aeronautics and Space Engineering Board, Committee for the Assessment of NASA's Space Solar Power Investment Strategy, Aeronautics and Space Engineering Board, "Laying the Foundation for Space Solar Power: An Assessment of NASA's Space Solar Power Investment Strategy." (National Academies Press; Washington, D.C. USA). 2001.

[15-6] These Space Solar Power systems concepts were discussed in Chapters 3 and 4.

[15-7] This amount did not include the cost of developing a reusable launch vehicle.

[15-8] It is interesting to note that within ten years (before 2010), a roadmap very similar to the 2000 SSP roadmap had been adopted by the Government of Japan; see the "Basic Space Law" at: http://www.kantei.go.jp/jp/singi/utyuu/basic_plan.pdf

[15-9] See: http://en.wikipedia.org/wiki/Iterative_and_incremental_development, for additional information concerning "iterative development." For information on "spiral development," see: https://acc.dau.mil/CommunityBrowser.aspx?id=37330.

[15-10] The road mapping approach used by the NIAC study built upon the approach used in the 2011 International Academy of Astronautics (IAA) "First International Assessment of Space Solar Power."

[15-11] One such test was performed over a distance of 148 km in the U.S. state of Hawaii in Spring 2008. In Chapter 3, Figure 3-5 presents photographs taken of the solar-powered microwave power transmission test equipment on location on the crest of Haleakala on the island of Maui in May 2008. The photo on the left is of the WPT equipment being tested in an anechoic chamber by Prof. N. Kaya of Kobe University; the photo on right is of the integrated experiment (including solar power) being tested in Hawaii. This test was sponsored by Discovery Communications, Inc., and was performed by an international team comprising from Japan, Kobe University (led by Prof. N. Kaya) and from the US, including Dr. F. Little and others of Texas A&M University, and Dr. N. Marzwell (formerly of the NASA Jet Propulsion Laboratory). J. Mankins was the team leader for the project.

[15-12] The Principal Investigator for this test was SPS-ALPHA NIAC Phase I project co-investigator Dr. Massimiliano Vasile.

[15-13] There are a great many good references on the topic of the standard life cycle for space systems projects. A good initial discussion published by NASA's Jet Propulsion Laboratory may be found at: http://www2.jpl.nasa.gov/basics/bsf7-1.php

[15-14] This was articulated in some detail in the 2011 IAA "First International Assessment of Space Solar Power", referenced previously.

[15-15] There is a trade here; the lower the mass of the SPS platform hardware, the higher the installed cost per kilogram may be, and conversely, the lower the cost per kilogram, the higher may be the acceptable mass of the platform.

Chapter 16 - Afterward

The Case for Space Solar Power

> *…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. Because the innovator has for enemies all those who have done well under the old conditions, and lukewarm defenders in those who may do well under the new."*
>
> *Niccolo Machiavelli (c. 1513)*
> *In The Prince*

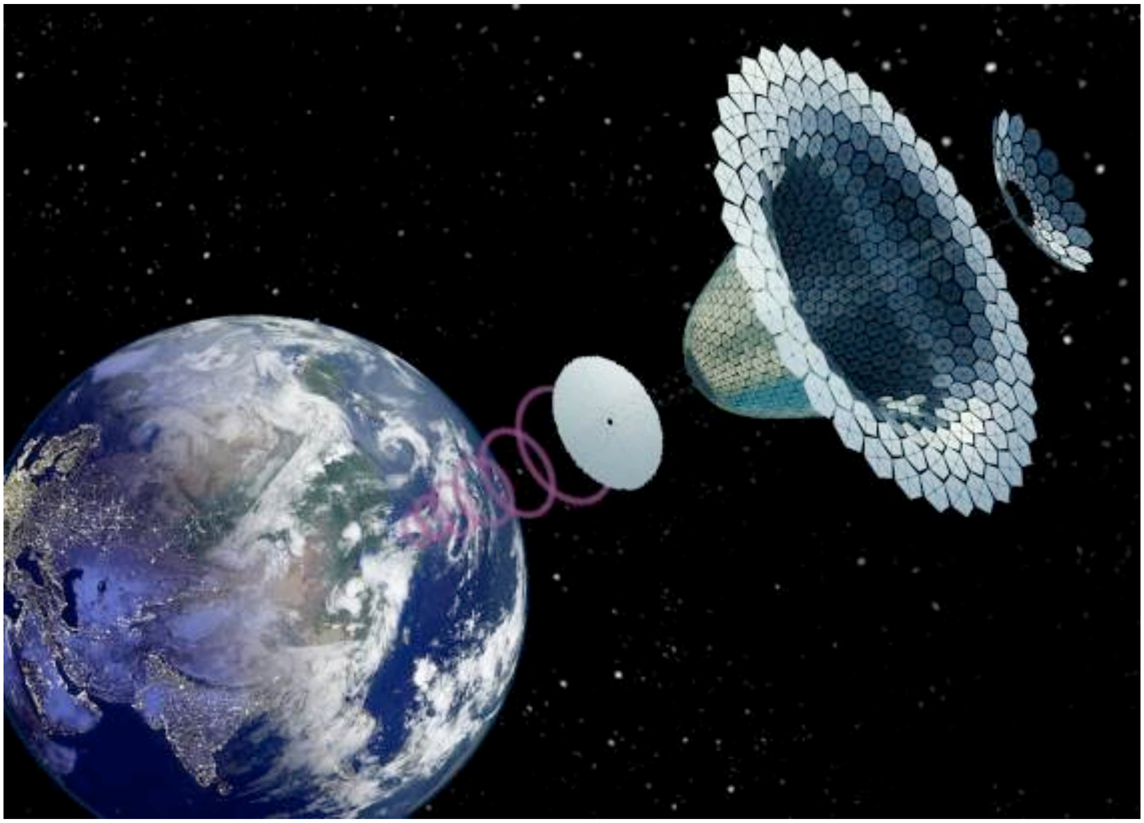
At an altitude of 22,240 miles above the Earth (some 35,786 km in metric units), a great platform orbits: collecting with vast, mirrored wings the continuous torrent of sunlight always available in space, redirecting and focusing that energy onto concentrating photovoltaic solar arrays that convert it into electrical power. With great efficiency, this tremendous platform uses the power of the Sun to generate a coherent stream of radio energy, and then wirelessly transmits that power with minimal losses down to highly efficient receivers the size of airports on the ground. The platform high in space gathers in over 5,000 megawatts of sunlight, and delivers – day and night – over 2,000 megawatts of clean, near zero-carbon electrical power to customers as needed, anywhere within an area the size of a continent or more.

On the Earth, the energy may be routed at large scale into the electrical grid as baseload power or it may be sent to one or more receivers to meet peak power needs. Alternatively, energy from the Solar Power Satellite may be transmitted to premium "niche" markets and provide power where it is particularly needed (and profitable), or it may be used to enable the annual production of 100s of millions of gallons of almost carbon-neutral synthetic fuels. (See the figure on the next page for one conceptual illustration.)

This is the vision of Space Solar Power.

The history of human civilization is recorded in the architecture and infrastructure that characterized each successive era. The pyramids of ancient Egypt, the roads of Rome, the Great Wall of China, the Panama Canal: each presents silent testimony to the central role it played in meeting the economic, spiritual, or security interests of the society from which they emerged. At their best, these monuments have been not only awe-inspiring but also useful, providing invaluable service for centuries to the cultures that created them.

Figure 16-1 Conceptual Illustration SPS-ALPHA in GEO



Chief among these developments have been systems and infrastructures that embodied the most important advances of each age in power, transport, communications, and agriculture. Without the dramatic advances represented in these critical systems of the past two thousand years – especially in the available sources of power – the world would be a drastically poorer and harsher home for a much smaller human population. However, the accelerating global consumption of dominant, affordable, and available energy sources will soon present fundamental challenges. In less time than has passed since the founding of Jamestown, or Shakespeare's penning of *The Tempest*, today's stupendous global reserves of oil, natural gas and coal will have been consumed.

Fossil fuels will not suffice to power human progress for much longer; but that is not to say that fossil fuels will "run-out". Rather, the real question is a tactical one: when will world production permanently fall behind global demand? When that happens, prices must rise – perhaps sharply, and probably permanently.

While humanity rapidly consumes irreplaceable fossil resources, we are also profoundly altering local environments, the chemistry of the ocean, and, in the view of the great majority of scientists, the climate of the world itself. Photographs of the sky over Beijing on a hot summer day – dark with particulates and unburned hydrocarbons and dangerous to the young and the elderly – illustrate graphically that the air pollution that once plagued London, Los Angeles, and other cities has not gone, but only relocated. Delivering the energy needed by modern civilization using fossil fuels releases enormous volumes of greenhouse gasses – over 2 pounds (1 kilogram) of carbon dioxide for each kilowatt-hour generated by coal. Global average temperatures are rising, as are ocean surface temperatures and insurances premiums for coastal areas.

These issues – the environment locally and the climate globally –raise additional concerns about the long-term sustainability of the energy and transportation infrastructures that have enabled the modern world.

The importance of abundant and affordable energy in space exploration and development is equally clear. Current missions of exploration and scientific discovery are narrowly constrained by a lack of energy. Future, more ambitious missions will never be realized without new, reliable, and less expensive sources of energy. Even more, the potential emergence of new space industries such as space tourism, manufacturing in space, Solar Power Satellites (SPS), and others will depend on reductions in the cost of power in space just as much as they will on progress in space transportation.

Recent studies and technological advances suggest that large-scale Space Solar Power systems may enable progress in both arenas during the next several decades. Of course, there are technological and engineering hurdles that must be surmounted to someday make large SSP systems a reality. Diverse technologies must emerge from the laboratory and be applied in space systems. Some of these involve space transportation, solar power generation, wireless power transmission, robotics, structural concepts and materials, and others. Nevertheless, there are potential benefits in the offing that seem to many to make challenging even these daunting technical barriers worthwhile – and perhaps essential. Unfortunately, the political and programmatic hurdles faced by Space Solar Power often seem even greater than the technical difficulties to be faced. The great engineering and technologies projects of the past century provide important lessons – both good and bad – that bear directly on this challenge.

This book examined the history, the challenge, and the promise of Space Solar Power, beginning with the invention of the SPS concept by Dr. Peter Glaser of Arthur D. Little some 40 years ago, and the development in the 1950s-1970s of various key technologies by gifted engineers such as Bill Brown of Raytheon. In addition, there have been great advances in various relevant technologies in the past 20 years. This book summarizes some of those advances – while highlighting the technical hurdles that remain. In the context of historical examples, it also suggests new pathways along which to advance the vision of almost limitless, clean energy for use here on Earth and up in space. Of course, as with any major new concept for energy, there are policy, regulatory, market, and programmatic issues to consider. These include safety considerations, cost issues, and spectrum allocation to name a few, as well as alternative systems approaches. The book also examined these considerations at a high level.

Ultimately, this book has recommended a path forward: how Space Solar Power might be realized during the coming decade. Solar Power Satellites are not a topic for the indefinite future; not merely science fiction for decades to come. Rather, SPS might with adequate funding be developed and demonstrated within the next 10 years.

However, Space Solar Power has had a quirky history; it was invented almost 50 years ago, and yet many have never even heard of it. The technical feasibility of both the prospective space applications and of Solar Power Satellites delivering harvested solar energy to Earth have been affirmed over 30 years by various independent peer reviews. And yet there are those who believe that the feasibility of SSP is unknown.

During the past 40 years, while Space Solar Power for Earth has remained little more than a vision, power for space missions has remained both scarce and expensive: most satellites operate on less power than that needed to run a typical home in the U.S., many on considerably less. If SPS-ALPHA can be developed, solar power in the range of 100s MW to 100s GW could be harvested in space and delivered efficiently to markets on Earth, thus enabling energy-rich operations throughout the inner solar system – transforming all aspects of government and commercial space.

The SPS-ALPHA concept represents a very different architecture for SSP: a hyper-modular approach in which all platform elements can be mass-produced, and none are larger than a "smallsat." If adopted, SPS-ALPHA could enable significantly shorter development time, much greater ease of manufacturing at lower cost, and significantly higher reliability. Systems analysis results from the 2011-2012 NIAC Phase 1 study project suggest that SPS-ALPHA may be able to achieve economic viability. Following needed technology maturation and systems-level demonstrations using technologies currently in the laboratory, the first full-scale SPS-ALPHA should achieve a levelized cost of electricity (LCOE) close to commercial baseload standards (around 10¢ per kW-hr). With improvements in selected technologies, later platforms should reach fully competitive commercial energy (at less than 10¢ per kW-hr).

Solar Power Satellites based on SPS-ALPHA could deliver power on demand to more than 90% of Earth's population at locations across the globe. It would have a near zero "carbon footprint" and facilitate reaching greenhouse gas (GHG) emission reduction goals. Affordable and continuous solar energy delivered on large scale from SPS to the U.S. and other markets would transform terrestrial power since no other "green energy" technology has similar potential to provide sustainable and "dispatchable" baseload power that is essentially immune to diurnal variations or to weather. SPS-ALPHA could enable a more rapid, effective, and affordable response to natural disasters and calamities (for example, the disastrous 11 March 2011 earthquake and tsunami in Japan).

It is occasionally argued that SPS must compete with ground-based solar, that it must be one or the other. Nothing could be further from the truth. Sustainable new energy sources – predominantly wind and solar – have made tremendous technical and market progress during the past 20 years. These advances resulted from government investments; like policy-driven economic incentives such as feed-in tariffs (FITs) and, in some cases, direct investments in specific systems. However, even though these recent sustainable energy entrants (following with their venerable uncle, hydro-power) are approaching parity with other sources in terms of cost, barriers remain that prevent wind or solar from providing more than about 15%-20% of total capacity. The reason is simple: wind, solar, and even hydro (to a much lesser extent) are all *variable* power sources. The amount of power that they can generate changes dramatically over the course of a year, a season, a day, or even an hour; this kind of variability is intolerable to power grid management.

Conversely, SPS delivers baseload power dispatched on demand and can do so almost continuously – "24/7" – to receivers across continents. This power would not be in competition with ground solar or wind; rather, Space Solar Power could be orchestrated to complement and supplement terrestrial sources when they are not available. As a result, availability of power from an SPS could enable significantly more ground solar and wind power to be deployed because SSP can be dispatched to where it is needed, and when.

As has been found in past studies and for other SPS concepts going back to the 1970s, ETO transportation remains a critical factor in realizing economically viable SPS for terrestrial markets. In-space transportation costs are also important, but appear closely tied to ETO cost; in other words, low-cost in-space transportation (from LEO to GEO) cannot be realized without low-cost ETO transportation.

In addition, there are a number of prospective civil, commercial, and security related applications of the SPS-ALPHA space systems architecture. These applications range from power for permanently shadowed regions at the lunar poles to near-term applications in various Earth-orbiting satellites where a large, low-cost aperture is required. In most locations across the inner Solar System, solar energy is available, sometimes continuously.

SPS-ALPHA would advance the capability to deliver affordable power to civil or commercial missions in space, at the Moon, or Mars, or at the small bodies of our Solar System. The availability of reliable, inexpensive, and continuous power at levels of 100s kW to 10s MW or higher would forever change the character of space systems, missions, and goals. Moreover, high power large apertures would be of great value for U.S. security space missions. Recent studies (e.g., for DOD NSSO) concluded that development of SSP systems and technologies, including SPS, would significantly benefit the security of the U.S. and its allies. Not only would space systems benefit, but benefits would also result from delivery of assured, affordable power to forward bases, military operations, markets, and allies. Ancillary SSP technologies – in areas such as space transportation, space communications, in-space construction, robotics, lightweight structures, etc. – would be of immense value to a wide range of civil / commercial space missions.

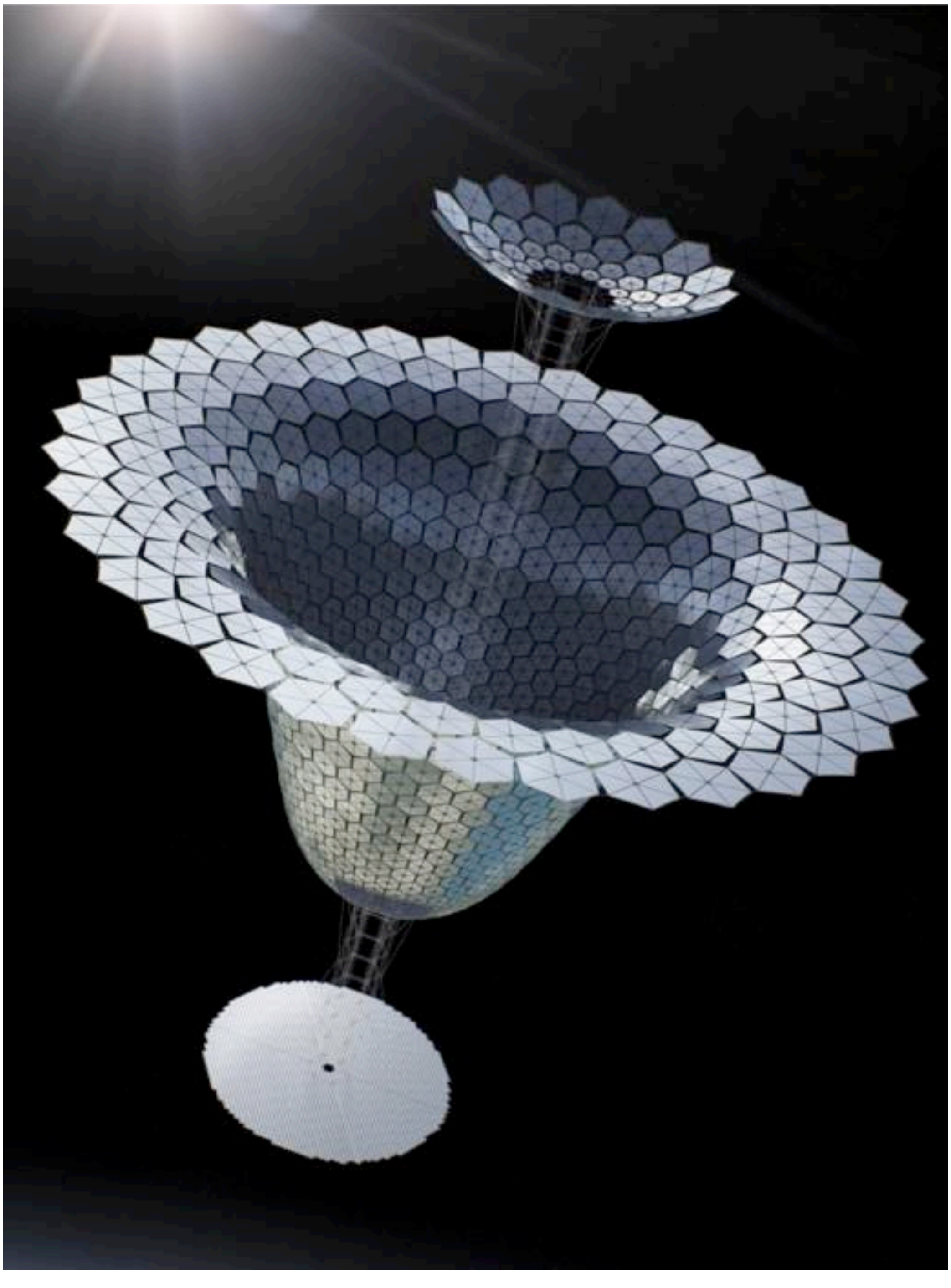
The roadmap to SPS-ALPHA is quite tractable, with investments on the scale of Boston's "Big Dig," or Europe's "Chunnel," or the 60-years of fusion R&D.[1] The hyper-modular architecture should enable fast-paced, relatively inexpensive steps forward, with a total cost for a scalable Solar Power Satellite pilot plant of about $5B and the first full-scale SPS of roughly $20B. These numbers are substantial, but compare well to the reported $100B cost of the International Space Station or the earlier 1970s-era estimates of roughly $300B-to-$1,000B (2013 dollars) to deploy the first SPS of the 1979 Reference System design.

SPS-ALPHA in particular and the hyper-modular approach to Space Solar Power in general are extremely promising and warrant both future consideration and R&D funding. Are there other ways to approach Space Solar Power, rather than SPS-ALPHA? Absolutely! However, for a variety of reasons, most – if not all of those that have been identified so far – are less promising, as we discussed in Chapter 4. There is no guarantee; the resolution of a number of systems, technology, and programmatic issues is critical to the future economical viability of SSP.

However, if those hurdles are surmounted (and I hope I've persuaded you that they can be), then a truly remarkable opportunity for energy on Earth and our future in space is at hand: this is the *Case for Space Solar Power*.

[16-1] There are various references for the numbers; such as: http://en.wikipedia.org/wiki/Big_Dig, http://focusfusion.org/index.php/site/reframe/wasteful, and http://en.wikipedia.org/wiki/Channel_Tunnel.

Appendices



Appendix A

Integrated SPS Timeline[1,2]

Year(s)	Milestone Summary	Location of Milestone
1897	Nikola Tesla files his first patent application dealing specifically with wireless transmission.	USA
1925	Konstantin Tsiolkovski proposes using solar energy for space vehicles.	Russia
1953	Isaac Asimov publishes "Caves of Steel" in Galaxy Magazine, a novel in which he mentions the concept of beaming solar energy to Earth (from the orbit of Mercury!).	USA
1957	Sputnik – the first artificial satellite – launched.	Russia
1961	William C. (Bill) Brown publishes his first paper on the idea of using microwave RF energy to transmit power wirelessly.	USA
1964	Bill Brown demonstrated on Walter Cronkite's CBS Evening News a wireless microwave-powered model helicopter.	USA
1965	The concept of the Solar Power Satellite (SPS) first conceived by Dr. Peter Glaser of Arthur D. Little, Inc.	USA
1968	SPS concept formally proposed by Dr. Peter Glaser in a paper, "Power from the Sun: Its Future," presented at the Intersociety Energy Conversion Engineering Conference (IECEC); Patent Filed.	USA
1968-72	Early systems studies and analysis of SPS concept [by industry groups, Energy Research and Development Administration (ERDA), NASA, and various other groups].	USA
1973	US Patent for the Solar Power Satellite granted to Dr. Peter Glaser.	USA
1973-1974	Japan starts the Sunshine Plan to develop renewable energy sources. Japan's Plan includes, as a long-term objective, the development of the Solar Power Satellite.	Japan
1975	NASA JPL conducts high power (34 kW) microwave wireless power transmission (WPT) experiment at the Goldstone DSN Station in the Mojave desert, California – a record that has never been broken.	USA

Year(s)	Milestone Summary	Location of Milestone
1977-78	The Sunsat Energy Council is formed to advocate SPS, with Peter Glaser as its first President; members include Boeing, Raytheon, Grumman, and other major aerospace firms.	USA
1978-80	“Concept Development and Evaluation Program” (CDEP) is conducted by ERDA (later renamed the Department of Energy, “DOE”) and NASA.	USA
1979	ESA Study "European Aspects of Solar Power Satellites"	Europe
1979-1980	Independent reviews/critiques of the CDEP conducted by the Congressional Office of Technology Assessment (OTA) and National Research Council (NRC).	USA
1981	US SPS studies are terminated by DOE and NASA.	USA
1981	First flight of the NASA Space Shuttle on April 12, 1981	USA
1983	Japanese researchers test microwave transmission through the ionosphere using a sounding rocket – the “MINIX” Experiment.	Japan
1985	SPS’85 – international conference held in Paris, France	F/international
1986	Space Shuttle Challenger disaster, killing all aboard; NASA Space Shuttle Program stands down for 2 ½ years.	USA
1986	NCOS (National Commission on Space) in the US recommends need for an “ideal space enterprise” to further the commercial development of space—and identifies SPS as one ‘speculative’ candidate venture.	USA
1986	SPS’86 - international conference held in Paris, France; it is the first international Solar Power Satellite conference.	F/international
1987	Project "Stationary High Altitude Relay Platform (SHARP)" for WPT by Canadian Ministry for Communication	Canada
Late 1980s	Lunar soil utilization studies include SPS	USA
1989	President George H. W. Bush announces the Human Exploration Initiative (later renamed the Space Exploration Initiative, or “SEI”) on the steps of the Smithsonian Air & Space Museum in Washington, D.C. - July 20, 1989.	USA
1990	Inclusion of Space Power sessions into IAF conferences	International
1991	SPS’91 - international conference held in Paris, France (“SPS 2000” Paper is awarded a prize as the best proposal);this is the second international SPS conference.	F/international

Year(s)	Milestone Summary	Location of Milestone
1992	SPS'92 – international conference held in Rio de Janeiro, Brazil (in association with the "International Conference on Aid and Development")	Brazil/international
1992	International Space University (ISU) Space Studies Program Summer '92 Design Project on Solar Power Satellites	USA/International (held in Kitakyushu, Japan)
1993	Project ISY-METS, WPT and space plasma interactions	Japan/ International
1993	WPT'93 Conference, held in San Antonio Texas	USA
1993	UNESCO World Solar Summit in Paris	F/international
1994	KEPCO (Kansai Electric Power Co.) and Kobe University Study on terrestrial WPT applications	Japan
1994	Microwave garden experiment (Microwave exposure experiment for plant growth, Advanced Industrial Science and Technology)	Japan
1995	WPT'95 Conference, Kobe Japan	Japan/ International
1995-97	The "Fresh Look Study" conducted by NASA (participants include multiple NASA centers, industry, and universities)	USA / NASA
1997	SPS'97/WPT'97 – international conference, held in Montréal, Canada	Canada / International
1997-98	CSA (Canadian Space Agency) implements the Canadian Space Power Initiative.	Canada
1998	NASA's "Space Solar Power Concept Definition Study" – provides an independent, NASA-internal examination of the results of the "Fresh Look Study."	USA / NASA
1998	WPT technology demonstration conducted at La Réunion Island, France.	France
1999	ESA Study "Space Exploration and Utilization" (including SPS)	Europe
1999-2001	NASA's "Space Solar Power Exploration Research and Technology" (SERT) Program	USA / NASA
2001	WPT'01 Conference, La Réunion Island	France
2001	"Laying the Foundations for Space Solar Power: An Assessment of NASA's Space Solar Power Investment Strategy," U.S. National Research Council	USA / NRC

Year(s)	Milestone Summary	Location of Milestone
2001-2003	NASA-NSF (National Science Foundation) Jointly-Sponsored SSP technology research program	USA
2002	World Space Congress (WSC) held in October 2002, in Houston, Texas; a major international exhibit presents the results of US and international SPS R&D efforts.	USA / International
2003	NASA Space Shuttle Columbia disaster on February 1, 2003	USA
2003-2005	European SPS Program (Phase 1: Comparison of Ground Solar Power and Space Solar Power)	Europe
2004	US President George W. Bush announces the Vision for Space Exploration (VSE) at NASA Headquarters, in Washington D.C. – January 14, 2004.	USA
2004	SPS'04 – international conference, held in Granada, Spain (Organized by ESA)	Europe / International
2006	Furoshiki Sounding Rocket Experiment successful; implemented by international team involving JAXA (ISAS)-Kobe University-University of Tokyo-University of Vienna (ESA)	Japan / Europe
2007	Massachusetts Institute of Technology (MIT) hosts an international workshop on SPS with the goal of determining the status of the concept and its potential both to meet future carbon-neutral energy needs, and as a possible project at MIT.	USA
2007	U.S. National Security Space Office (NSSO) charters a preliminary assessment of space-based solar power with the goal of better understanding and characterizing this future energy alternative.	USA
2008	Discovery Communications, Inc. (parent company of the Discovery Channel) sponsors a first-of-a-kind end-to-end experiment testing solar-powered wireless power transmission from the crest of Haleakala (Maui Island in Hawaii) to slopes of Mauna Loa (Hawaii Island).	USA-Japan
2008-2011	International Academy of Astronautics (IAA) Commission III (Space Technology and Systems Development) organizes the first international assessment of Space Solar Power.	USA-Japan-Europe / International (10 Countries)

Year(s)	Milestone Summary	Location of Milestone
2009	The IAA Space Solar Power assessment organizes "SPS 2009" at the Ontario Science Center in Toronto, Canada in cooperation with SPACE Canada (a non-profit organization in Canada) and the National Space Society (a non-profit organization in the US).	USA-Canada-Japan / International
2009	Kobe University (Kaya) team demonstrates active microwave beam steering using retro-directive phase control at the SPS 2009 Workshop and International Symposium.	Japan-USA-Canada
2010	Kobe University (Kaya) team tests the SPS 2009 active microwave power transmission system in Hawaii (from Mauna Loa on the big island of Hawaii to Haleakala on Maui).	Japan-USA
2011	IAA Space Solar Power assessment final report published in September 2011.	US-Canada-Japan / International (10 Countries)
2011-2012	NASA's Innovative Advanced Concepts (NIAC) program sponsors a major new SSP Phase 1 study project on a new type of systems architecture: SPS-ALPHA (Solar Power Satellite via Arbitrarily Large Phased Array). There are co-investigators in Japan and at the University of Strathclyde, Glasgow in Europe. Phase 1 Final Report published in September 2012.	USA-Japan-Europe
2013	IAC 2013 in Beijing, China; Space Solar Power Plenary Event; China broadly announces interest of CAST and CAS in Space Solar Power.	China
2013	The "*Case for Space Solar Power*" is published.	USA

[A-1] In addition to various papers, personal experience, etc., the references for the timeline include: the "ESA Advanced Concepts Team" website; "A Civilian Space Travel and Tourism Guide" website; and the "spacefuture.com" website.

[A-2] Since circa 1990, the annual International Astronautical Congress (IAC) has included a session on SPS, organized by the International Astronautical Federation (IAF) Power Committee.

Appendix B
The 2011-2012 Phase 1 NIAC Project

Introduction

During 2011-2012, NASA's Innovative Advanced Concepts (NIAC) program supported a preliminary Phase 1 project to investigate a transformational new approach to space solar power: SPS-ALPHA (Solar Power Satellite by means of Arbitrarily Large Phased Array). To deliver energy to Earth, SPS-ALPHA would typically be based in a geostationary Earth orbit (GEO), where it would intercept sunlight using a collection of individually pointed thin-film mirrors, convert that sunlight across a large radio frequency (RF) aperture into a coherent microwave beam, and transmit the power to markets on Earth or in space.

Goals & Objectives

The goals of the project were to establish the technical and economic viability of the SPS-ALPHA concept to an early TRL 3 – analytical proof-of-concept – and to provide a framework for further study and technology development. The objectives of the innovative advanced concept project were to: (1) Conduct an initial end-to-end systems analysis of the SPS-ALPHA concept in order to determine its technical feasibility; (2) identify and assess in greater detail the key technology challenges inherent in the architecture (including figures of merit for each critical technology area); (3) Test in supporting parallel experiments some of the key figures of merit for SSP, and use the results to inform systems modeling efforts; (4) conduct an initial evaluation of the economic viability of the concept (as a function of key performance parameters); and (5) define a preliminary roadmap for the further research and development of the SPS-ALPHA concept.

The result of the project was to advance the current technology readiness level (TRL) of this novel conceptual approach from TRL 1 / TRL 2 (physical principles established and basic concept formulated) to early TRL 3 (experimental and/or analytical proof of key functionality in the laboratory). As planned, this project was largely analytical with selected supporting experiments.

Systems Analysis Approach

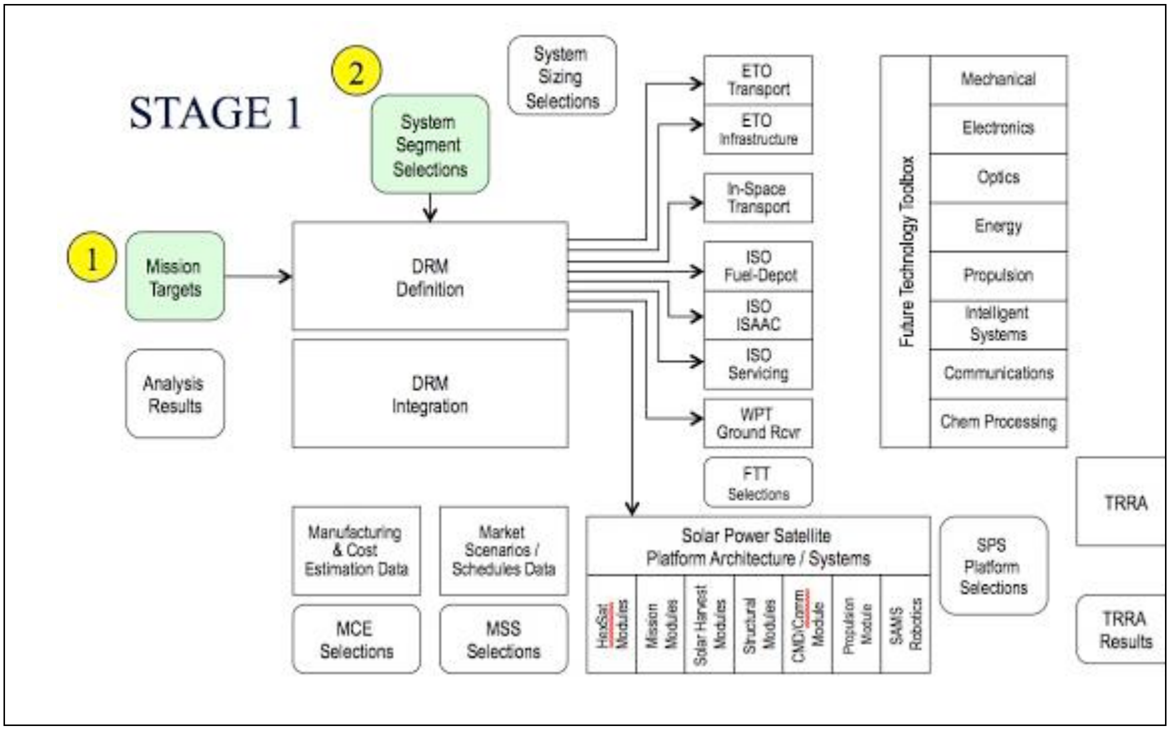
The SPS-ALPHA Phase 1 NIAC project used a systems analysis approach described as "ACES" [Advanced Concepts Evaluation System (Mark-1)]. ACES is a methodology for analysis, supported by a suite of Microsoft Excel-based analysis tools – some of which have been newly re-developed for the NIAC SPS-ALPHA Phase 1 Project. ACS requires the use of a modular, multi-workbook environment to perform quantitative analysis of alternatives (AoA) for various SPS-ALPHA system design choices and to evaluate how technology choices and/or investment decisions impact their performance, mass and cost. In order to provide a consistent basis of existing and projected technology data for use in these evaluations, ACES incorporates the idea of a comprehensive "Future Technology Toolbox" (FTT) that can be updated regularly by supporting technologists. The ACES approach enables integrated Technology Readiness and Risk Assessments (TRRAs) across and among systems options and "technology clusters." (See Section 8 for further information.)

ACES depended on the construction of an SPS design reference mission (DRM) through selection of modeled system elements from various architecture segments within the SPS-ALPHA platform. In addition, very high-level "models" were defined of key supporting infrastructures such as Earth to orbit (ETO) transportation, in-space transport, etc. See Figures B-1, B-2, and B-3 for a graphic overview of the ACES systems analysis approach.

The methodology also depends on the construction of integrated DRM timelines, including key missions/markets, within which life cycle costs and economics can be evaluated. Although ACES was formulated specifically to accommodate SPS-ALPHA analyses, with additional appropriate system models, similar AOAs could be conducted for a wide range of other advanced concepts for various space missions and markets. As illustrated in Figure B-1, Stage 1 of the ACES methodology includes two steps:

> Step 1: Select SPS Mission Targets (e.g., GEO-based SPS to deliver Energy to Markets on Earth, etc.); these selections were made as part of the market definition study; and
>
> Step 2: Select system segments to be used in the case study (e.g., what type of ETO, In-Space Transportation, etc.); these selections were made in the Space Segment Model (SSM), described below.

Figure B-1 SPS-ALPHA Phase 1 Systems Analysis Stage 1



Stage 2 of the ACES methodology includes three additional steps:

Step 3: Select System Sizing Option (e.g., ETO Transportation Payload Sizes, In-Space Transportation Payload Sizes, etc.); these selections were made in the individual supporting infrastructure "models;"

Step 4: Select Sizing Options for the SPS-ALPHA Platform (e.g., Diameter of Main Array, size of HexSat Modules in Main Array, etc.); these selections were made in the SSM; and

Step 5: Selection of Technologies from FTT for use in System Modules (e.g., choice of PV for use in SPG, choice of timeframe for Initial Use of Technology, etc.); these selections were made in the SSM.

Stage 3 comprises five additional steps:

Step 6A: Select an Alternative Market Scenario and associated schedules; these choices were made in the macroeconomics modeling spreadsheet;

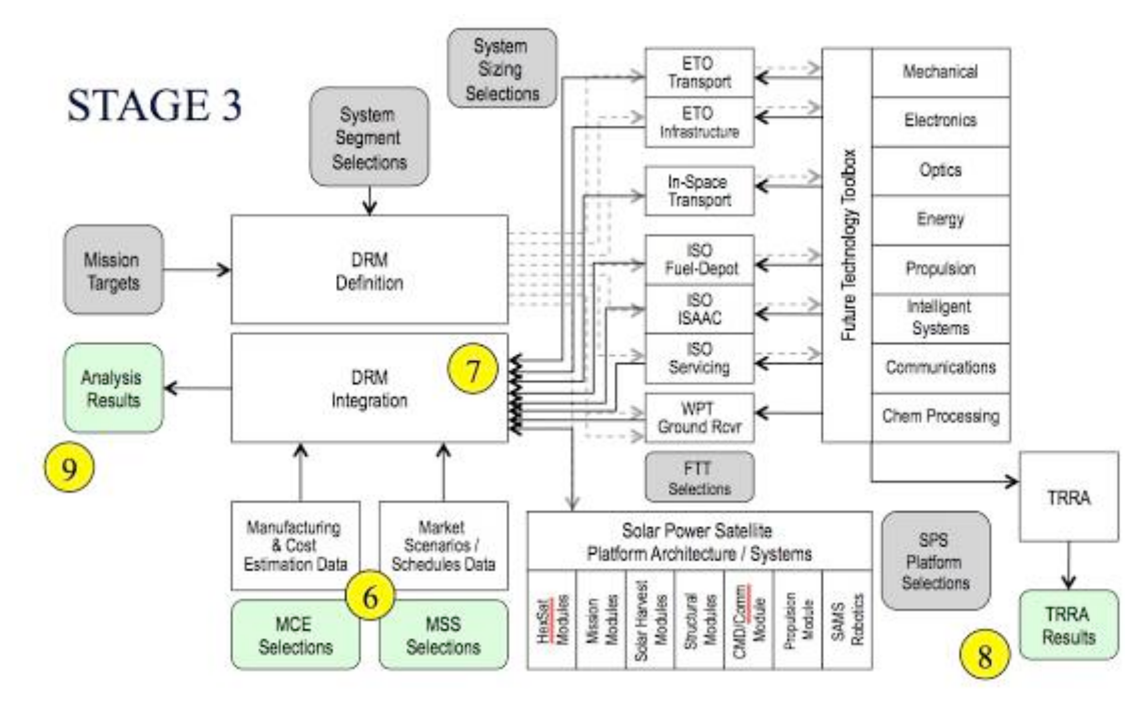
Step 6B: Select a Manufacturing Scenario and associated schedules (based on schedule choice in 6A); this choice is made in the macroeconomics modeling workbook;

Step 7: Given the above selections/linkages, "RUN" DRM Integration;

Step 8: Develop the Integrated Technology Readiness and Risk Assessment (TRRA) and review results produced (given technology selections and schedule choices); and

Step 9: Review the various parametric results produced based on running DRM Integration and the System Segments in the context of the Schedule, Manufacturing, and Market Scenarios.

Figure B-2 SPS-ALPHA Phase 1 Systems Analysis Stage 2

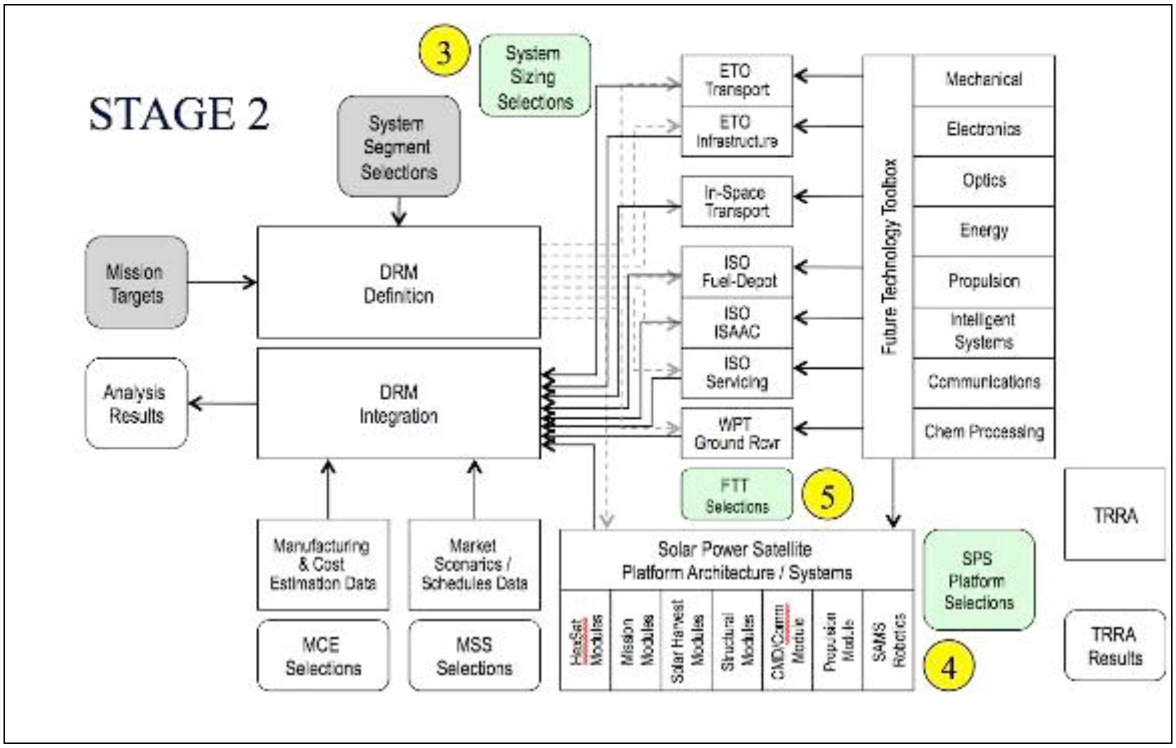


In addition to the above stages/steps, a final pseudo "Stage D" comprises an iteration of the above to accomplish the required Analysis of Alternatives (AoA) as needed.

NIAC Phase 1 SPS-ALPHA Project Systems Analysis Tool

Although the ACES methodology was used in this Phase 1 NIAC project, the brevity of the schedule and the limitations of available resources necessitated combining existing and new software tools to perform the required systems analysis studies. An existing spreadsheet-based software tool — the SSM (Space Segment Model) developed under NASA's SSP Fresh Look Study in 1995-1997) — was reviewed and updated to incorporate the SPS-ALPHA concept.[1] The updated SSM is a physics-based modeling tool that incorporates automated re-sizing of various systems design features to satisfy high-level architecture and systems requirements given specific technology parameters.

Figure B.3 SPS-ALPHA Phase 1 Systems Analysis Stage 3



In addition to the refreshed SSM tool, a new macroeconomic model (also spreadsheet based) was developed for the project. This tool performs cost estimation and incorporates quantified external market considerations (e.g., energy prices, policy incentives, etc.) to enable analyses of the overall economic performance for the several SPS-ALPHA DRMs. Finally stand-alone spreadsheet tools were developed to model non-platform systems (e.g., robotics, space transportation, etc.) to allow sizing (e.g., numbers of vehicles, launches, robotic systems, etc.) driven by the results of SSM modeling.

NIAC Phase 1 SPS-ALPHA Project Results

The results of the NIAC Phase 1 study may be found scattered throughout this text and in the final report, which may be downloaded from the NASA Innovative Advanced Concepts (NIAC) web site at:

http://www.nasa.gov/pdf/716070main_Mankins_2011_PhI_SPS_Alpha.pdf

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[B-1] Dr. Harvey Feingold, formerly of SAIC and the developer of the Space Segment Model (SSM) for the 1990s NASA Fresh Look Study of Space Solar Power, was the lead for this activity within this NIAC Phase I project.

Appendix C

Frequently Asked Questions (& Answers)

Introduction

With any new technology, there are always various reasons that can be offered as to why it should not be pursued or why some slight alternative to a proposed concept would be somewhat better. Solar Power Satellites are certainly no exception. This Appendix poses and answers a few of the "But what about...?" questions that are most frequently raised concerning SPS. Most such topics are discussed in the body of the text and are not repeated here. The questions and answers that follow fall into the following broad topics:

Ground solar power versus space solar power
Cost
Wireless power transmission
Responsibility for SPS
Reliability, servicing and maintenance; and
Other questions

Topic Area: Ground Solar Power vs. Space Solar Power

Question: *What about…ground solar versus Space Solar Power?*[1]

The 'tough question' asked most frequently in discussing Solar Power Satellites is also the easiest to answer: why not just use ground solar power? The immediate answer is: where it makes economic sense, you should always use ground solar power!

Historically, solar energy technologies have been much more expensive than other options – in terms of both cost per installed watt and cost per delivered kilowatt-hour. These costs have come down dramatically in recent years as the scale of commercial PV (photovoltaic) production has increased (particularly in China). However, there are a number of remaining limitations on the infusion of this important technology into power grids around the world.

Obviously, PV arrays only generate power during daylight hours. In addition, when the sun is low in the sky the intensity of the sunlight received is lessened by the mass of air through which it must travel. (Even at noon and at the equator, sunlight on Earth is only about 75% as intense as sunlight in space near Earth.) On average, the net result of these effects is that on average only about 6 hours of ‘full intensity’ sunlight can be received by a PV array even on the best of days. Figures 1 and 2 in Chapter 1 provide clear illustrations of the overall effects of these three factors on the total energy that can be delivered by a ground solar power system compared to the total amount of solar energy available in space at the Earth’s orbit.

Concentrated Solar Power (CSP) uses intense, focused sunlight to heat a material such as a molten salt to drive a heat engine (e.g., a Brayton cycle engine), which in turn makes electricity. CSP is more expensive than PV, and can usually be deployed only in large (multi-MW) scale. However, it has a distinct advantage: the heated material can remain hot – and be used to generate electricity – for some hours after sunset. In other words, it combines power generation and energy storage in one system. The mirror array that concentrates the sunlight must be over-sized to gather extra energy during peak daytime hours, and the mirrors typically obscure one another in the morning and the afternoon (as the sun nears the horizon, a given mirror blocks the view of the sun of the one to the east or west of it, depending), both of which add to cost.

As a result, CSP is not competitive with PV arrays as a supplement to conventional power supplies. Still, CSP might prove to be an interesting alternative to PV for large-scale baseload ground solar power in locations with large open areas and sufficient sunlight.

In most locations in North America, Asia, or Europe, bad weather and overcast skies can obscure the sun for days or even weeks at a time. At present, this makes it economically impractical for PV arrays (or CSP) to provide “baseload” power (i.e., the nearly continuous large-scale power that enables civilization). In fact, rooftop solar arrays or local larger-scale ground solar power systems are typically limited to about 10%-20% of the total power generating capacity available to utility managers.

Question: *What about stupendously huge solar arrays in the desert?*

The vast majority of humanity does not live in the desert; most live in temperate areas, well to the north or south of the equator, and far away from large deserts. Over one billion live on various islands – many scattered across the Pacific Ocean. Still, the concept of placing huge solar arrays in a desert where the weather is almost always clear is certainly possible. Two candidates that are often mentioned include the Sahara Desert in North Africa and the deserts of the US Southwest in North America: hundreds of gigawatts (GW) of photovoltaic (PV) arrays could be deployed in these locations. If it is possible, why hasn’t it been done, or at least started?

In my view, there are really two principal reasons. First, the huge array will go into night more or less all at once, taking 100s of GW off the grid as darkness falls. Near sunrise and sunset, sunlight intensity falls off significantly. Even without weather effects, providing baseload power would require energy storage of roughly 1,200,000,000 to 1,800,000,000 kilowatt-hours for every 100 GW of generation capacity. At costs of between $100-to-$300 per kW-hr, that would represent an investment of $120B-$480B for each 100 GW of power, over and above the cost of the solar array, which would need to be doubled or tripled in area to allow for charging the energy storage system during daylight hours. CSP systems improve the situation, as discussed above. However, even desert areas occasionally get overcast skies: energy storage must be provided for those times as well. As mentioned above, this is the main reason that PV arrays are used as increasingly cost-effective supplements to other energy sources.

Second, there are "national economy-scale" risks associated with this approach. For example, the power generated will typically be remote from the relevant markets (e.g., the Sahara Desert versus markets in Europe); as a result, massive long distance and very high voltage power lines must be deployed. Such power lines would represent both a significant additional cost as well as a single point of failure for the system as a whole. Moreover, a hostile government or even a non-State based independent group could threaten these power lines – endangering the economy of 100s of millions of customers. Similarly, in many cases the power plants that might be deployed would be in other countries, introducing an additional layer of geopolitical and economic complexity and uncertainty. Given the events of the "Arab Spring" during 2011-2013, would anyone in Europe wish to have 100s of GW of essential baseload power located in the countries that comprise North Africa?

Topic Area: Cost

Question: *Isn't this unaffordable? How could anyone pay for this?*

SPS will always be big – just as hydroelectric plants are usually big – but they need not be excessively expensive. Past SPS concepts involved vast projected costs. However, more recent studies indic,"ate that SSP systems have the potential to be no more expensive than other major infrastructure projects of the past several decades – including Boston's "Big Dig", the French-English Channel Tunnel (a.k.a, the "Chunnel"), or China's Three Gorges Dam project. These projects were on the scale of $20B to $40B each, and were undertaken by variously organized government and industry teams. Moreover, the development of Space Solar Power systems involves the maturation of technologies with a wealth of intermediate and alternative applications – including low cost launch systems, advanced robotics, etc. – all of which means that the macro-economic cost-effectiveness of an investment in SSP could be far greater than an investment in low-tech alternatives. (Although considerable technology development and engineering of new systems are needed, no new physics is needed for modular Space Solar Power to be achieved.)

Moreover, it seems likely that no single government would "pay for this." The maturation of needed technologies would likely involve resources from both government (including various agencies) and the private sector – as is usually the case. Although the U.S. government would likely be a customer for, and/or in some case an owner of, mature SSP systems for its own purposes, most SSPS would be purchased and deployed using funds from various governments or large-scale industrial players, just as is the case for the energy industry today.

Question: *What about energy payback?*

Inevitably, when discussing new energy options – including Space Solar Power – one must address the time required for the new system to produce enough power to pay for the energy cost of making and deploying that system. Certainly, some have questioned if the energy costs of Solar Power Satellites are too great to overcome. Stated a little more technically, the questions revolve around the issue of the 'energy payback ratio' for SPS, whether that ratio is greater than 1, and if so, how much greater. SPS energy costs include the energy that goes into manufacturing the pieces of the Satellite, launching those pieces from Earth, and finally moving them to their operational position in geostationary Earth orbit. As it happens, this issue is not an issue: the energy payback time for SPS is remarkably brief.

The energy required to manufacture SPS is about the same as that to manufacture solar power systems for use on the Earth. However, each kilogram of SPS mass delivers (because of nearly continuous sunlight) about 4 times more energy per kilogram than the same kilogram on Earth. Hence, the energy payback time for the SPS platform will be no worse than one-quarter of the time for a similar power capacity PV array on Earth. What about the energy cost of transportation?

A reasonable estimate for the total mass of an advanced technology SPS satellite is about 10 kilograms per kilowatt of power that the spacecraft is capable of generating on the ground. As a result, the mass of a 1 GW (gigawatt) SPS system would be about 10,000 tons (i.e., 10,000,000 kg or about 22,000,000 pounds). Then, the net energy cost of launching this system into space would be given by

$$\text{Kinetic Energy} = \text{KE} = 1/2 * M * v^2$$

Where "M" is the mass of the platform and "v" is the velocity squared. With a mass of about 10,000 tons, a total velocity in orbit of 7,000 meters per second, and assuming an efficiency factor of 25% (i.e., assuming that 4 times more energy is needed than is converted into velocity in orbit), then the total energy cost of getting the SPS into low Earth orbit is about:

$$9.8 * 10^{14} \text{ Joules; or } 98{,}000{,}000{,}000{,}000 \text{ Joules}^{2}$$

This sounds like a lot, but is only about 270,000 kilowatt-hours.

Estimated conservatively, the energy cost of moving the pieces of the SPS from LEO to GEO would be about half the energy cost of getting the SPS elements into LEO in the first place. With this assumption, the total energy cost of the installed 1 GW SPS may be estimated at 400,000-600,000 kW-hrs, which is a small fraction of the energy cost of manufacturing the platform itself. Hence, the total energy payback time is still considerably less than that for a comparable power capacity terrestrial solar array.

Question: *Can space transportation be cheap enough to make SPS viable?*

The simple answer is: "yes." Chapter 7 presents a detailed discussion of this topic. Although the cost of transportation from Earth to GEO today is about $20,000 per kilogram (or some $9,000 per pound), there are no fundamental barriers in physics or engineering to realizing dramatic reductions in the cost of space launch. Moreover, the early-to-mid timeframe stages of modular SSP development – including technology flight experiments, sub-scale prototypes, and even pilot systems – can all be launched with existing vehicles at costs ranging $10,000 per kilogram down to about $3,000 per kilogram.

For transportation of commercially-competitive SSP systems in the longer term, the higher traffic rates, higher efficiency in-space propulsion, and reusable vehicle systems make it possible to achieve launch costs of $500 per kilogram down to $200 per kilogram. There are several new systems approaches now being developed, any one of which might accomplish this goal (for example, commercial firms such as SpaceX and its proposed reusable Falcon 9 first stage).

Topic Area: Wireless Power Transmission

Question: *Is it safe?*

Another question often asked is this: would Solar Power Satellites be safe? The question that must be asked in response is: safer than what? None of the energy technologies that are in use today is perfectly safe. Although nuclear power systems are sometimes cited as dangerous, the most deadly of humanity's energy sources continues to be coal. On average, thousands of individuals are killed each year in coal mining accidents, tens of thousands are killed in traffic accidents, thousands die of lung disease caused by use of various fuels, thousands of birds and bats are killed each year by wind turbines, and so on.

Would power from an SPS be as safe as or safer than other sources of energy? The answer is yes, depending on how the power is transmitted to the ground. As we discussed in Chapter 4, there are solutions (such as high power lasers at frequencies that would pass through the atmosphere) that would not be safe. However, for microwave WPT (wireless power transmission) at around 1-10 GHz frequency, and with peak energy densities limited to roughly $1/5^{th}$ to $1/10^{th}$ that of summer sunlight (or about 200 down to 100 watts per square-meter), power transmission should be perfectly safe. This assertion was validated in a series of studies performed as part of the 1970s SPS program to determine whether WPT using microwaves was safe. (Bees and other animals were tested to see if they would be adversely affected, they were not.)

Also, in the late 1990s, research at the NASA Ames Research Center (Dr. Jay Skiles) examined the effects of low-level microwaves on typical plant species; it reaffirmed the likelihood that WPT either below the receiver (where the beam density is very low), and at or beyond the edges of the beam will have little or no effect on plant species.

Certainly, additional research is needed; however, properly managed WPT from an SPS should be less hazardous than many other energy technologies in wide-scale use today.

Question: *Won't it be almost as hard to send the energy to Earth is it will be to deploy the SPS hardware in space?*

No, that's simply untrue. WPT – even over long distances – involves simple, well-understood physics and engineering. Certainly, diverse materials and components need to be improved (particularly improvements in the efficiency of devices, reductions in the mass of systems, etc.); however, the problems of fusion power or genetically engineered algae to produce fuels at high efficiency are much more technically challenging than WPT from space to Earth. Diverse projects going back to the 1960s have demonstrated WPT over various distances. Wireless power transmission will not difficult from the research standpoint.

Question: *Won't the microwave transmission encounter insurmountable problems in passing through the atmosphere? Won't it harm birds?*

The answer will in most cases be "no" – if the WPT system is designed properly to use a frequency at which the atmosphere is transparent and at power levels that are safe. If the wavelength is between 2 and 20 centimeters (about 1-10 inches), the atmosphere and even rather severe weather will not interfere with wireless power transmission. Also, because the size of the transmitter at this wavelength must be large and the power level is well known, the intensity of the transmission cannot harm animals or people.

Question: *Can an SPS be used as a weapon?*

It depends on the details, but the answer is "no" in most cases. Space Solar Power systems can be designed such that they cannot focus their transmitted power at a location other than their intended receiver on the Earth. Moreover, these systems can be designed such that WPT from an SPS does not have high enough intensity at a single location on the ground to cause damage to buildings or people. However, design choices matter: as discussed elsewhere, there are some approaches to SPS and WPT – such as high intensity and high power lasers – that would be harmful. (It is my view that such systems should not be developed.) And, although SPS and WPT systems can be designed with multiple, redundant safeguards, as with all major sources of energy (e.g., natural gas, gasoline, nuclear power), the technologies underlying SSP could be developed separately for defense applications.

Question: *What if the beam "drifts" over a city?*

The system can be designed to make this almost impossible. Past innovations (e.g., an idea called a 'retro-directive phased array') make it next to impossible for future power transmissions to be directed toward any target unintentionally. Of course, as with all energy technologies, Space Solar Power systems must be designed with multiple, redundant safeguards; future technology developments should focus on this as well as other operational needs for SSP systems.

Topic Area: Responsibility for SPS

Question: *Who would develop SPS?*

Government, Industry, and Universities would each have important roles to play for SSP to become a reality. Government must organize and promote the solution of international considerations, such as spectrum allocation. Government and Industry must both play a role in the development and demonstration of key technologies for initial systems. Government and industry must also work together to establish critical international standards,

In addition, universities must conduct research to find technical solutions that can improve the cost effectiveness of initial systems in the far term, (delete) while training the future generations of engineers that would be needed to establish a major new energy source. (This has always been the case.)

Question: *In the US, Why isn't DOD doing this? or DOE? or NASA?*

DOD (including the USAF) has a requirement to assure the availability of future energy sources. Moreover, there are numerous commonalities between the technologies needed for SSP and the technologies already being developed by the DOD for various USAF and other space and ground applications. These commonalities strengthen the opportunity represented by SSP and will ultimately reduce the 'opportunity cost' associated with pursuing SSP as compared to other options that only satisfy ground-based, domestic energy needs.

As for NASA, the U.S. space agency is focused exclusively on space science and exploration to satisfy broad cultural objectives (plus a modest ongoing investment in aeronautics technology R&D). It has no policy goals and no organizational interest in developing technologies or systems (such as SSP) to aid the U.S. economy or assure future energy security. NASA only invests in commercial system developments when those programs are targeted strictly on accomplishing NASA's own goals for science and/or human space flight.

Conversely, in the US, the Department of Energy (DOE) is focused exclusively on ground-based systems to meet future energy needs. Other than production of radioisotopes (such as Plutonium) to fuel the 'nuclear batteries' needed by various robotic probes, DOE has no current policy goals to develop technologies or systems (such as SSP) that would operate in space.

Question: *Is a special government agency or organization needed?*

It is possible that some special government agency, or department within an existing agency, will be needed. Certainly in the US no current government organization has the assigned responsibility to pursue SPS solar; such an assignment is critical to success. This assignment might require a new agency; however, further examination of policy options is needed. Examples of such an organization (Government-to-Government) might include the current International Space Station (ISS) organization and the International Thermonuclear Experimental Reactor (ITER) organization as well as the International Telecommunications Satellite Consortium (INTELSAT) organization of the 1960s.

Topic Area: Reliability, Servicing and Maintenance

Question: *What if there is a systems failure? Isn't it true that SPS systems in space could not be serviced?*

The simple answer is, "no, that's nonsense." The same architecture and technology that enable assembly of the SPS – particularly the hyper-modular architecture presented here – also ensure that the platform can be serviced when there are failures. If an SPS can be assembled, then it can be serviced; and if it cannot be serviced then it cannot be assembled in the first place.

Question: *Would Space Solar Power be reliable*?

It can be; however, once again it depends on the design. There are numerous ways to design a large and complex system comprising other, smaller systems. In some cases, one may have a series of unique subsystems – each playing their part, like "actors" in a play – in a larger system. However, for key roles (such as the leading lady), there are likely to be understudies as well, backup actors that are called into operation only if the primary system fails (or just needs a day off). A large system can be quite 'fragile.' For example, a system-of-systems can be prone to problems if it is neither inherently robust (with substantial margins already designed into key aspects of the system) nor inherently redundant (with 'understudies' ready to step in immediately when needed). For even an otherwise robust system-of-systems, the whole can be laid low by an "Achilles Heel" – a single point of failure that can bring down all the rest.

For modular systems of the right design, exceptionally high levels of reliability can be achieved if the design used avoids an "Achilles Heel." For such systems, multiple (essentially identical) elements are used to achieve some purpose. Up to some natural limit, increasing the number of elements can actually increase the reliability of the overall system-of-systems. This is the case with the hyper-modular architecture of SPS-ALPHA presented here.

Question: *Won't SPS be especially vulnerable to attack?*

All energy infrastructures are vulnerable to attack, some more than others. In the case of SPS, the key assets are placed some 22,240 miles (i.e., 35,786 kilometers) away in space; they are therefore invulnerable to conventional forms of attack, unlike existing energy sources. Many of the energy infrastructures upon which society depend – dams, pipelines, high voltage power lines, nuclear power plants – are more or less vulnerable to improvised threats by a determined individual or group. SPS, on the other hand cannot be reached except by nations, and any attack could be readily traced back to its source.

In addition, one business model for Space Solar Power would involve sharing the ownership and the services of any given SPS, or SPS industry, among the key stakeholders in various countries, thus mitigating the risks by assuring that all, or at least many, of those with the means to harm a satellite in GEO have a lot to lose if it should happen.

Question: *Won't solar arrays and other systems fail faster in space than on Earth? Won't that lead to short lifetimes and high costs?*

The answer is "yes and no." There are some components – such as PV cells – that will degrade in the radiation environment of space faster than on Earth. However, there are many others (including the great majority of the mass of the platform) that will most likely last almost indefinitely in space. As an example, look at the Voyager spacecraft, it launched more than 35 years ago and is still operating beyond the edge of our Solar System.

Micrometeorites and orbital debris that might impact the SPS and cause damage are also issues. Also, away from low Earth orbit (LEO), the existing risk of impact is much lower at present. SPS systems and the concept of operations (CONOPS) must be chosen so as to minimize the production of new orbital debris. Fortunately, with a hyper-modular architecture such as SPS-ALPHA there are no "single" points of failure. Impacts will cause damage, but it will be mostly inconsequential and will only occasionally require repairs.

No high technology system on Earth operates for decades without regular maintenance (even solar arrays on Earth must be cleaned frequently). And this is precisely the strategy for those components of a modular SPS architecture that do fail or degrade with time: regular maintenance and replacement. (See Chapter 8 for more information on this topic.)

Question: *Won't Solar Power Satellites be vulnerable to solar flares?*

Perhaps this will be an issue, but probably not. SSP systems can almost certainly be designed with electrically isolated electronics that can be protected from solar flares. It is possible that during such events, services from an SPS would be interrupted. Future technology development should focus on this as well as other operational needs for SSP systems.

Question: *How long would an SPS last before it would have to be decommissioned? What happens after the end of the lifetime of an SPS?*

SPS have the potential to operate almost indefinitely with proper repair and maintenance. Readers may remember the story of "my grandfather's ax." Namely, "I inherited my grandfather's ax from my father. Of course, he had to replace the handle twice, and I had to replace the head…but it's still my grandfather's ax…!" The highly modular systems concepts involved in a modern SPS would easily allow individual elements of the satellite to be replaced on a regular basis. A typical SPS module might operate for 15-25 years (based on more than 40 years of experience from communications satellites based in GEO).

Past studies have shown that replacing about 3%-5% per year of an SPS has little effect on the economic performance of the platform. This depends on two factors. First, the overall SPS system must operate for more than 10 years. Second, the servicing operations must be able to occur without taking the SPS "off-line" for an extended period. Hence, once the initial construction is completed and following the first few years of operation, a given SPS would operate for as long as desired – much like a hydroelectric dam – with only a small percentage of the platform being replaced and/or repaired each year. Much like the aqueducts of Rome, the Suez Canal, or the walls of Constantinople, a properly maintained Solar Power Satellite (properly maintained) might well provide energy to terrestrial markets for a century or two, or perhaps longer.

Topic Area: Other Questions

Question: *Won't sending solar energy to Earth add to global warming?*

Another question that often arises in casual conversation concerns the effects of transmitting some solar energy that would otherwise have missed Earth and passed by 'harmlessly' in space. The worry is that the additional solar energy taken from space and delivered to the surface will contribute significantly to the overall warming of the Earth.

Actually, the net warming effects due to the release of greenhouse gases by burning fossil fuels is so great that no renewable energy source – including Solar Power Satellites – can begin to compete. Also, the total energy the Earth receives continuously from the Sun is so stupendously large that it is hard to imagine a scenario by which even a large SPS constellation could contribute more than a tiny fraction of it. For example, near Earth the energy output from the Sun has an intensity of about 1360 watts per square meter.[3] Earth's diameter is about 11,000 km – or 11,000,000 meters; the resulting area that the Earth presents to the sun is about 9.5 x 10^{13} square meters, or some 950,000,000,000,000 square meters.

As a result, the Earth intercepts continuously from the Sun about 1,300,000,000,000,000,000 watts – which is about 1,300,000,000 GW – and is more than 250,000-times greater than the total electrical power generating capacity of human civilization in the year 2010 (which was roughly 5,000 GW). Even if thousands of Solar Power Satellites (each generating one gigawatt or so) were to be deployed, the total energy sent to Earth would have no meaningful effect on the total thermal balance of our planet. The effects of greenhouse gas emissions resulting from the burning of fossil fuels are vastly greater than those that might result from using solar energy from space.

Question: *What happens when an SPS goes into Earth's shadow?*[4]

The answer to this question depends on where the platform is placed. Clearly, in most low earth orbit (LEO) locations, an SPS would spend about 1/3rd of the time in Earth's shadow. (And, by the way, in all cases, Earth's surface is about 75% water – so an SPS in LEO would have to contend with both shadowing and a lack of receivers!) However, in a high Earth orbit above the equator such as GEO (geostationary Earth orbit), during the vast majority of the year the SPS never passes through Earth's shadow.

In the spring and fall (March and September around the time of the "equinoxes," to be specific), for about six weeks the platform will pass briefly through Earth's shadow, right around local midnight on the ground below. Roughly 22 days before the equinox, the satellite passes through the edge of the shadow for a few moments. This period increases until the maximum time in shadow – about 70 minutes – occurs right around the 21st of the month, then it decreases again, going back to zero about 22 days after the equinox. If the average time in shadow is 35 minutes, then over a period of some 44 days (twice per year), the total time a given SPS would spend in shadow will be about 51 hrs, out of a total of roughly 8,766 hours per year. That's a bit less than 0.6% of the time, always at local midnight.

Stated differently, a Solar Power Satellite in GEO will be in the sunlight 99.4% of the time (annually); it will be shadowed in a highly predictable way around midnight for several weeks in March and September each year, up to a maximum of a bit more than one hour on the worst day.

Question: *What about building SPS from extraterrestrial resources*?

A topic that is often discussed when considering Solar Power Satellites is that of making the satellites from pieces fabricated from extraterrestrial resources; in other words, system elements manufactured from materials found beyond the Earth. Of course, there are two natural sources for raw materials from which one might manufacture Solar Power Satellites: the Moon and near-Earth asteroids.

In the case of lunar-derived materials, the basic concept would involve the manufacture of SPS system elements from lunar materials. Following their local manufacture, these system elements would be launched from the lunar surface and delivered to geostationary Earth orbit. Near-Earth approaching asteroids are another possible source of raw materials from which to manufacture SPS. These small bodies – leftovers from the earliest origins of the planets at the beginnings of our solar system – are easily accessible from geostationary Earth orbit (at least in terms of energy).

In the heyday of space visionaries, the L-5 Society and the subsequent Space Studies Institute (SSI) were formed. Based in Princeton, New Jersey in the U.S.A., the SSI under the leadership of Professor Gerald (Gerry) O'Neil considered the long-term future of humanity in space. They arrived at the idea of large space settlements, perhaps constructed at the Earth-Moon Lagrange Point known as "L-5" where thousands or tens of thousands of individuals could live in almost Earth-like conditions. The inhabitants of these large 'space habitats' would be actively engaged in the construction of large, 'stick built' Solar Power Satellites[5] – the revenues from which would provide the basis for an economy in space.

Many of the challenges of Earth-to-orbit and in-space transportation costs <u>might</u> be resolved through the successful use of extraterrestrial materials in future SSP systems. The advantage derives from the possibility of launching SPS elements electromagnetically from the Moon, rather than using chemically-fueled rockets from the Earth (see the discussion of space transportation in Chapter 7). These approaches seem to hold significant promise for the farther term, particularly once an SPS industry has been established. However, the infrastructure requirements of either lunar or asteroid mining in addition to manufacturing would seem – if placed in series with the initial development and deployment of SPS – to represent a high barrier to programmatic viability.

Overall, it is my view that building SPS from space resources is an option for the far term, rather than a way to get started.

Question: *Why now? Why hasn't SPS been developed already?*

30 years ago – even 10 years ago – the issue of energy was less urgent. Today, the price of energy has soared as the demand in the U.S. and various developing countries (China, India, etc.) has ballooned. In addition, the stability of key energy producing regions has diminished, while the long term availability of affordable and abundant fossil fuels is no longer certain. All told, there is a far more urgent need to successfully resolve a range of energy security issues than there was in the past.

Also, although the technology needed for highly modular SPS architectures was not available decades ago, advances have been made across the board since then. For example, in the 1970s, SSP concepts assumed 10,000 or more people living in space just to assemble SSP platforms. No such requirement exists today due to well-established advances in computing and robotics. Also in the 1970s, SPS studies assumed solar arrays with a efficiency of around 10 % (i.e., only 10% of the sunlight hitting the array was converted into electricity). Today, solar cells have been tested with efficiencies greater than 40% – and 50% efficiencies are being pursued. Taken together, the technology choices involved in past SPS concepts meant that they weren't capable of providing energy at a price competitive with ground market prices.

Finally, environmental concerns are far greater today than in the past. There is now a consensus that global climate changes are occurring with increasing impacts (financial and personal), and are largely the result of greenhouse gas accumulation in the atmosphere, with the carbon dioxide (CO_2) released during the combustion of fossil fuels as the leading cause. There was no such shared understanding and concern in the past.

As discussed in this volume, these concerns have resulted not only in increased government-sponsored R&D to create new, sustainable energy options, but also in economic incentives (such as tax credits, feed-in tariffs) that substantially enhance the market opportunity for new solutions (including SSP).

Question: *How much difference could it possibly make?*

SSP could make a tremendous contribution, but it will not meet all energy needs. No single energy source meets all the needs of industrial society today; this will certainly continue to be true in the decades ahead. For example, ground-based solar power will certainly provide a steadily increasing amount of energy, albeit intermittently. However, the deployment of large-scale, cost-competitive SPS in geostationary Earth orbit could provide from 10s of GW to many 100s of GW of clean, carbon-neutral energy globally.

[C-1] Mr. John Strickland (a former Director of the National Space Society and of the Sunsat Energy Council) has been examining the comparison between ground solar power and Space Solar Power for many years.

[C-2] Where "1 Joule "is equal to "1 kilogram-meter per second-squared," and "1 Joule per second" is equal exactly to "1 watt."

[C-3] Recall that a meter is just a bit larger than a yard: about 39 inches for a meter, versus exactly 36 inches for a yard. So, a square meter is a bit less than 10 percent larger than a square yard.

[C-4] Of course, the Moon will eclipse an SPS on occasion; however, such events will be rare and readily calculated. The same is true for solar arrays on Earth.

[C-5] See Chapter 10, concerning in-space assembly and construction for a discussion of the differences between 'stick-built' systems concepts and 'intelligent modular systems' approaches to SPS.

Appendix D

Glossary of Acronyms

Acronym	Definition
ACES	Advanced Concepts Evaluation System
ACS	Attitude Control System
ACT	(ESA) Advanced Concepts Team
AEHF	Advanced Extremely High Frequency
AFRL	Air Force Research Laboratory
AIAA	American Institute of Aeronautics and Astronautics
AIST	Affordable In-Space Transportation
a.k.a.	also known as
ALS	Advanced Launch System
AMLS	Advanced Manned Launch System
AoA	Analysis of Alternatives
AR&D	Autonomous Rendezvous and Docking
ARPA-E	(US DOE) Advanced Research Projects Agency-Energy
ASEB	(U.S. / NRC) Aeronautics and Space Engineering Board
AST	Advanced Space Transportation (Program)
B&P	Bid and Proposal
BCG	Boston Consulting Group
CAS	China Academy of Sciences
CAST	China Academy of Space Technology
CBP	Commercial Baseload Power
CDEP	(SPS) Concept Definition & Evaluation Program
CDR	Critical Design Review
CDS	Command and Data System
CER	Cost Estimation Relationship
CIPP	Commercial Intermediate & Peaking Power
CNT	Carbon Nanotube

Acronym	Definition
CommSat	Communication Satellite
CONOPS	Concept of Operations
COPUOS	(UN) Committee on the Peaceful Uses of Outer Space
CNDB	Civil Needs Data Base
COTS	COmmercial Transportation Systems
CPFF	Cost Plus Fixed Fee
C-PNP	Commercial PNP
CPV	Concentrator Photovoltaic
CSA	Canadian Space Agency
CSI	Controls-Structures Interactions
CSP	Concentrator Solar Power (usually solar thermal)
CSP	(TAMU) Center for Space Power
CSTS	Commercial Space Transportation Study
CTA	Connecting Truss Assembly
DARPA	Defense Advanced Research Projects Agency
DC	Direct Current
Δv	Delta-Velocity
°C	Degrees Celsius
°F	Degrees Fahrenheit
DIPS	Dynamic Isotope Power Systems
DOD	Department of Defense
DOE	Department of Energy
$	Dollars, US
DRDO	(India) Defense Research and Development Organization
DRM	Design Reference Mission
DSN	Deep Space Network
EADS	European Aeronautics Defense and Space Company
ELV	Expendable Launch Vehicle

Acronym	Definition
EM L1	Earth-Moon Libration Point L1 (and so on for EM L2, etc.)
EPRI	Electric Power Research Institute
ERDA	(US) Energy Research and Development Agency
ESA	European Space Agency
ESMD	Exploration Systems Mission Directorate
ESTEC	European Space Research and Technology Center
ETO	Earth-to-Orbit (Transportation)
ETS	(JAXA) Engineering Test Satellite
EVA	Extravehicular Activity
FESTIP	Future European Space Transportation Investigations Program
FET	Field Effect Transistor (Amplifier)
FIT	Feed-In Tariff
FLO	First Lunar Outpost
FLPP	Future Launcher Preparatory Program
FOM	Figure of Merit
FOS	Forerunner Operational Systems
FTT	Future Technology Toolbox
FTE	Full-Time Equivalent
GAO	General Accountability Office
GDP	Gross Domestic Product
GEO	Geostationary Earth Orbit
GHG	Green House Gas(ses)
GHz	Gigahertz
GLOW	Gross Lift-Off Weight
GN&C	Guidance, Navigation and Control
GPS	Global Positioning System
GSSPWG	(IAA) Global Space Solar Power Working Group
GW	Gigawatts

Acronym	Definition
HexBus	Hexagonal Ring Satellite Bus
HLLV	Heavy Lift Launch Vehicle
HMM	Human Mars Mission
HRST	Highly Reusable Space Transportation
HSM	HexFrame Structural Module
HTS	High-Temperature Superconductor
H/W	Hardware
HVCP	High-Value Chemical Product
HVDC	High-Voltage Direct Current (Power Line)
IAA	International Academy of Astronautics
IAC	International Astronautical Congress
IAF	International Astronautical Federation
IECEC	International Energy Conference and Engineering Conference
IISL	International Institute of Space Law
IMLEO	Initial Mass in Low Earth Orbit
IRR	Internal Rate of Return
ISAAC	In-Space Assembly and Construction
ISAS	(JAXA) Institute of Space and Astronautical Science
ISC	Integrated Symmetrical Concentrator
ISM	Industrial, Scientific and Medical (RF Bands)
Isp	Specific Impulse
ISRO	India Space Research Organization
ISRU	*In Situ* Resource Utilization
ISS	International Space Station
ISTP	Integrated Space Transportation Program
ISY-METS	International Space Year - Microwave Energy Transmission in Space
ITAR	International Trade in Armaments Regulations
ITER	International Thermonuclear Experimental Reactor

Acronym	Definition
ITU	International Telecommunications Union
JAXA	Japan Aerospace Exploration Agency
JPL	(NASA) Jet Propulsion Laboratory
JSC	(NASA) Johnson Space Center
kg	Kilogram(s)
km	Kilometer(s)
KPP	Key Performance Parameter
kW	Kilowatt(s)
kWh	Kilowatt-hour(s)
LCC	Life Cycle Cost
LC/MC	Learning Curve / Manufacturing Curve
LCOE	Levelized Cost of Electricity
LEO	Low Earth Orbit
LH2	Liquid Hydrogen
LLC	Limited Liability Company
LLO	Low Lunar Orbit
LMO	Low Mars Orbit
LOX	Liquid Oxygen
LS-ALPHA	Lunar Surface Power by means of Arbitrarily Large Phased Array
LSP	Lunar Solar Power
m	Meter
MARE	Modular Autonomous Robotic Equipment
MEO	Middle Earth Orbit
MHz	Megahertz
MIMIX	Microwave Ionosphere Nonlinear Interaction eXperiment
MIT	Massachusetts Institute of Technology
MMW	Multi-Megawatt
MPPR	Modular Push-me/Pull-you Robotic (Arm)

Acronym	Definition
m/s	Meters per Second
MSFC	(NASA) Marshall Space Flight Center
MT	Metric Tons
MW	Megawatts
Nanosat	Nano-scale Small Satellite
NASA	National Aeronautics and Space Administration
NASP	National AeroSpace Plane
NCOS	National Commission on Space
NIAC	NASA Innovative Advanced Concepts (Program)
NGLT	Next Generation Launch Technology
NLS	National Launch System
nm	Nanometers
NPV	Net Present Value
NRC	(US) National Research Council
NRL	(US) Naval Research Laboratory
NSF	(US) National Science Foundation
NS-PNP	National Security PNP
NSSO	(DOD) National Security Space Office
NSTS	National Space Transportation System
O&M	Operations and Maintenance
OECD	Organization for Economic Co-operation and Development
ORU	Orbital Replacement Unit
OSF	(NASA) Office of Space Flight
OTV	Orbital Transfer Vehicle
PAA	Primary Array Assembly
PACA	Propulsion and Attitude Control Assembly
PMAD	Power Management and Distribution
PNM	Premium Niche Market

Acronym	Definition
PNP	Premium Niche Power
PNV	Premium Niche Market
PSA	Primary Structure Assembly
PV	Photovoltaics
R&D	Research and Development
R&D3	R&D Degree of Difficulty
RADAR	Radio Detection and Ranging
Rcvr	Receiver
Rectenna	Rectifying Antenna
RDM	Reflector Deployment Module
RDPA	Retro-Directive Phased Array
RF	Radio Frequency
RFID	RF Identification Device
RLV	Reusable Launch Vehicle
RMS	Remote Manipulator System
ROI	Return on Investment
RPA	Retrodirective Phased Array
RTG	Radioisotope Thermoelectric Generator
s	Second(s)
SABRE	Synergetic Air-Breathing Rocket Engine
SAIC	Science Applications International Corporation
SAMS	Space Assembly, Maintenance and Servicing
SbOCT	Space-Based Optical Communications Terminal
SbSP	Space-based Solar Power
SDP	Space Demonstrations & Prototypes
SEI	Space Exploration Initiative
SE L1	Sun-Earth L1 Libration Point (etc. for SE L2)
SEPS	Solar Electric Propulsion System
SERT	(NASA) SSP Exploratory Research and Technology

Acronym	Definition
	(Program)
SES	Sustainable Energy Sources
SEU	Single Event Upset
SHARP	Stationary High-Altitude Relay Platform
SLS	Space Launch System
SmallSat	Small Satellite
SME	Subject Matter Expert
SNR	Space Nuclear Reactor
SPACE Canada	Solar Power Alternative for Clean Energy - Canada
SPE	Solar Particle Event
SPG	Solar Power Generation
SPS	Solar Power Satellite
SPS-ALPHA	SPS by means of Arbitrarily Large Phased Array
SRA	Solar Reflector Assembly
SSI	Space Studies Institute
SSM	Space Segment Model
SSP	Space Solar Power
SSPA	Solid State Power Amplifier
SSTO	Single-Stage-to-Orbit (RLV)
STAS	Space Transportation Architecture Study
S/W	Software
TAMU	Texas A&M University
TBD	To Be Determined
TFD	Technology Flight Demonstration
TFE	Technology Flight Experiment
TMD	Technology Maturation and Demonstration
TMS	Thermal Management System
TNV	Technology Need Value
TPS	Thermal Protection System

Acronym	Definition
TRA	Technology Readiness Assessment
Xmttr	Transmitter
TRL	Technology Readiness Level
TRRA	Technology Readiness and Risk Assessment
TSTO	Two-Stage-to-Orbit (RLV)
T/W	Thrust-to-Weight Ratio
TW	Terawatt
TW-hr	Terawatt-hour
TWT	Traveling Wave Tube
UN	United Nations
USA	United States of America
USAF	United States Air Force
USSR	Union of Soviet Socialist Republics
VSE	Vision for Space Exploration
VTHL	Vertical Take-off / Horizontal Landing (SSTO)
VTVL	Vertical Take-off / Vertical Landing (SSTO)
WPT	Wireless Power Transmission
WTO	World Trade Organization

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