THE SPACE POWER GRID

Narayanan Komerath, Nicholas Boechler

School of Aerospace Engineering
Georgia Institute of Technology, Atlanta, GA, USA 30332-0150
Narayanan.komerath@ae.gatech.edu

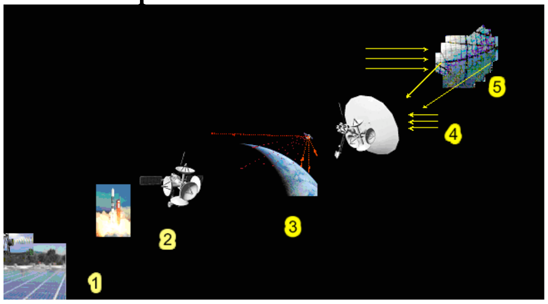
This paper lays out an approach to develop Space Solar Power, with a small initial investment, a rising market, early revenue generation, and an evolutionary path to full Space-based power generation. The key idea is to use space assets initially for a global power exchange, establish the infrastructure, and then add space-based power as technology advances and revenue flows in. The system develops through 3 Phases, going from a Space Power Grid to an Augmented Grid to Full Space Solar Power. All conversion equipment is in low earth orbits, while ultralight collectors are in higher orbits. Large technical uncertainty persists in the efficiencies that can be obtained with beamed power. In the short term, efficiency may be only half that of the best terrestrial transmission, but the system can open markets that are now inaccessible. It also enables "green" power plants on earth. In the long term, as power from space dominates the system, the efficiency is better than today's best terrestrial. Previous work on retail power beaming from space, and current ideas on small-scale terrestrial demonstrations, fit within the system. Within the context of a global enterprise, this route provides an economically viable path to full space solar power.

INTRODUCTION

Power from space[1] has long held the promise of abundant electrical energy on Earth, and the technology to accomplish this appears to be quite within reach. The insurmountable barrier is the huge cost of placing large satellites at Geosynchronous Earth Orbit (GEO) and the corresponding receivers on earth, before any revenue can be derived to support the enterprise. This cost is estimated to be $300 Billion or greater[2]. Thus the problem to be solved is how to develop an evolutionary approach where revenue generation starts early and with relatively small investment, and leads to full-scale Space Solar Power (SSP). Several step-by-step approaches have been advanced to reduce the cost to first power[3], but all involve the ultimate use of satellites and beaming from GEO or beyond, or lunar power plants and earth-based receivers. Thus, the cost of earth-based receivers continues to be large, as does the marginal cost per installed watt of power in space.

In this paper, we present an approach that inverts the thinking for the initial steps. No single aspect of this approach is new or fundamentally untested. The novelty and uniqueness are in integrating the various ideas and components in a logical, self-supporting sequence. The arguments for the approach are composed of economic, socio-political and technical aspects. Being a large space infrastructure project, it is assumed that this is an international enterprise[4]. Phase 1 is the basic Space Power Grid (SPG), consisting of 36 to 96 satellites in sun-synchronous and equatorial orbits at 800 to 1200km. These satellites will transact power between points on earth, taking advantage of time-zone, day-night and climate differences. Phase 2 commences when the SPG breaks even, and replaces the constellation with satellites augmented with solar collectors and converters. In Phase 3, large, ultra-light solar collectors in medium-height orbits (a few thousand

Figure 1: Phases of the Space Power Grid
1.Microwave converters/ transmitters installed.
2. Phase 1: SPG starts with 36 satellites
3. Phase 2: Augmented satellites: A-SPG
4. Phase 3: Ultralight collector beams sunlight to SPG: Full Space Solar Power



kilometers) will beam broadband sunlight to the LEO converters. Features of this system are:

Throughout, the Space Power Grid handles the power distribution.

The infrastructure to be placed in medium orbits (and not in GEO) consists of ultralight collectors, and does not include the heavy equipment to convert sunlight to microwave or laser, and hence there is up to two orders of magnitude saving in launch/ installation cost. Also, this phase comes after the rest of the infrastructure is installed and has positive cash flow.

The system is dynamic, consisting of LEO satellites, and thus requires constant control, switching and large power transactions, like a modern-day terrestrial grid. These will benefit from technologies taken from modern cell-phone adaptive antennae that track individual users using digital signal processing. There are obvious similarities to beam weapon pointing problems as well.

All receivers and transmitters are of small size, except for the ultralight reflectors that collect sunlight at the medium-height orbits.

The transfer of energy to LEO, the long leg in the full SSP phase, is accomplished using visible sunlight, so that large receivers are not needed. However, the transfer from the bright to dark side of Earth, and the atmospheric transfer, are accomplished using microwaves.

The system will only achieve half the end-to-end efficiency of the best modern-day terrestrial grid in Phase 1, but at the final full Space Solar Power Phase, will be more efficient than today's grid. Thus revenue generation at the beginning will depend on power transactions to locations where the cost of power is more than 200% of the off-peak levels in the US.

The paper is organized as follows. First, the market opportunity is described. Next, the prior work on space solar power is summarized. This is followed by the description of each of the Phases of the concept. System architecture options are next described. The economics of the system are revisited, and the results to-date are summarized.

Argument for the Space Power Grid

The arguments in favor of SSP are well-known: solar power is clean, steady and reliable, and there is plenty of it available. A square kilometer collects 1.3GW. With conversion losses, this can amount to some 500MW of electrical power, equivalent to a modern nuclear reactor.

Advanced industrial nations have a huge installed power grid, using high-voltage lines that incur very low transmission losses. This has already been paid for. In addition, most nuclear plants have fully paid off their investment. On the other hand, "Green" energy sources such as wind and solar plants have to be located in high deserts, mountain ranges, and coastlines – regions with poor transmission infrastructure. "Green" sources are fundamentally unsteady, and hence cannot compete for "baseload" status, or command the same price for their product as established fossil, nuclear or hydroelectric plants. On the other hand, in many countries, delivery infrastructure is ill developed. Today, hydrocarbon fuel prices are 3 times what they were a very few years ago. Switching to synthetic hydrocarbons is not an option because of rising penalties for carbon emission. The net economic costs have been estimated to range from \$160 to 260 per ton of CO2 released into the atmosphere.

Even in industrialized societies, there is a very large fluctuation in the cost of power, through a typical day. Landis[5] has shown that during peak hours in New York city, the cost per kilowatt-hour rises to over \$0.4, compared to \$0.06 off-peak. Bekey and Boudrealt[6] propose a system in Geosynchronous orbit to relay power from plants in Canada to customers in Japan, where power costs are high. Other market opportunities are listed below.

- The Space Power Grid can smoothen power plant output and turn them into "firm baseload sources"[7] that command higher prices.
- Energy producers can sell their large or fluctuating excess capacity to distant customers.
- Distributors can receive "Green" power matched to increasing local demand due to development.
- The SPG can reach areas at extreme latitudes.
- Places lacking infrastructure for power generation or distribution, such as islands, deep forests, mountainous areas and desert communities are good prospects to use the SPG.
- Disaster-hit areas, where mobile, air-delivered receiver stations can quickly restore power.
- Rapid-deployed military forces
- In-space resources to which power can be beamed from Earth. Competing power costs in this market are very high, and hence this can be lucrative for the SPG.

Market size

World primary energy consumption[8] was 433 quadrillion BTU and rising at 2.2 percent annually. By 2030, the total market is projected at the equivalent of 45600GW installed capacity, at the usual 50% average operating level. Today over 50% of primary power generation is fossil, and the proportion that is converted to electricity is relatively small. This proportion could rise dramatically if clean, cheap, electricity became available. By 2025, global North American electricity consumption is projected to be 23072TWh, of which the US will account for 5025TWH.

There are over 49000 electric power plants in the world, generating a total of 2812 GW, indicating an average capacity of around 57MW. Approximately 1100GW of this is in 4144 North American plants, at an average of 265MW. The average of the other 45000-odd plants is only 38 MW because developing countries invest in micro-power plants suitable to smaller community/ rural electrification projects, while plants in the industrialized nations are concentrated into very large units. There are 774 "new generation" plants in the US, producing an average 310 MW of "green" energy. Newer nuclear plants (and wind farms) coming up around the world appear to be designed at a 700MW level on average.

Retail Market Size is considered essentially unlimited, as the demand for energy is growing rapidly on earth, and the paying power of customers rises as energy becomes available for them to implement development in their areas.

Sizing Decisions Based on Market Considerations

Since wireless power beaming is currently only half as efficient as conventional wire transmission, most of the above plants will beam only part of their output. North American "Green" suppliers are likely to beam up large amounts of energy during peak generation periods. This energy may be distributed in small amounts to a large number of receiving stations. Given the 10:1 size ratio of plants between North America and the rest of the world, and given that each new plant may have 3 major receiving hubs, a ratio of 100 retail output beams to 3 large input collectors appears reasonable. Also, a 250MW capacity per satellite is adequate to soak up the entire output from all but the largest plants, or substantial output from three at a time.

PRIOR WORK

Earlier SSP concepts used GEO PhotoVoltaic array satellites and kilometer-sized terrestrial microwave collectors. A 1995 "Fresh Look" study[9] proposed more radical concepts[2], but the basic issue of launching the conversion equipment (1kg/kw) remained. The National Academy of Engineering[10] recommended funding SSP development in 2001, but even the imagined 10-fold launch cost reduction was far from sufficient. The Space Solar Power Workshop argued for a "SunSat Corporation"[11] which would pool resources and interests of all those involved in the SSP business. They claimed that a mass-market approach – over 5000 launches to GEO - would cause a collapse of launch costs. A 2004 Los Alamos study[12] looked at scenarios enabled by space elevators, but even at $100/kg launch cost, $0.12/kwH energy price and $100/acre receiver land cost, SSP was competitive only by using direct-conversion optical rectennae. Criswell[13] has argued for locating collectors and conversion equipment on the Moon, pointing out that a transmitter with very large synthetic aperture can be built on the Moon for less than the cost of one solar power satellite. Clearly, none of these concepts offer viable paths today.

Carbon Credits

Restrictions on fossil fuel burning, and credits for using carbon-free "green" energy sources, are estimated to net $160 to $260 per ton of CO2 released into the atmosphere[14], equivalent to $0.04 to $0.066. The US DOE provides one "Green Tag" per MW[15] to producers of clean alternative energy. These can be traded on the market.

The Space Power Relay System

Bekey and Boudreault (1998)[16] studied a Space Power Relay System (SPRS). This system would beam power from a plant in Canada to a set of membrane reflectors, to distribute power to one or more receivers located in Japan. A variation of their system had ten membrane reflectors on one spacecraft, connected by independently steerable lightweight tethers. The SPRS assumed that power generated in North America could be sold at a large premium in Japan, thus offering an enterprise with an Internal Rate of Return of 35%. The frequency chosen for beaming was 35GHz. The receiver array diameter is on the order of 1kilometer. Receivers were located in large water reservoirs, which stored hydroelectric energy to smooth out power delivery fluctuations. Bekey et al also included the benefits of the Kyoto Protocol in calculating economic viability.

SPS2000: Dynamic Retail Transmission

Japanese engineers[17,18] advanced SPS2000[19] in the early 1990s. They used dynamic transmission and reception, implied by low earth orbit (LEO) satellites. One concept was to put a series of 300m-diameter solar collector/converter satellites at 1100km-high equatorial orbits and beam 2.45GHz power in a wide cone, illuminating a 300km diameter region. Receivers in this region would use the power to charge small devices, and skipping from one satellite to another over time. One interesting finding from this work was that a 300m solar cell and transmitter array was projected to have a mass under 1400kg. Nagatomo[20] described elements of a prototype system compatible with low-cost ground rectennae coupled with storage to deal with intermittent satellite arrival and short overhead duration.

Brown[21] showed that microwave rectannae could be designed with essentially 100% beam capture, and 85 - 90% conversion efficiency. Shaposhnikov[22] discusses design of discontinuous antennae optimized for long-distance beaming from space. Smart antenna arrays[23] today use digital computing to focus on thousands of individual moving cell-phone customers in real-time. Similar technology could presumably tune transmitter arrays to channel much of the power into beams aimed at active customers, so that coverage of a large area is not inefficient.

SELECTION OF SYSTEM PARAMETERS

Argument for High Frequency Beaming

The primary drawback of a space-based power beaming relay is its poor end-to-end efficiency. The efficiency of conversion[24] to and from useful forms of electrical energy (See Sims[25] for a discussion of the problems) awaits technological breakthroughs. The loss in capture of a beam is best remedied by going to high frequencies, which reduces the size of the antenna needed for near-100% capture.

Millimeter-wave technology is increasingly used in beamed weapons, with very high beam power and intensity. Benford and Dickinson[26] discuss applications to space propulsion and power beaming. At 220GHz, atmospheric absorption losses are as low as 5%, when beaming to and from high-altitude locations, and air breakdown is not an issue even at the very high intensities discussed there. Cloud cover greatly reduces transmission at these wavelengths. They showed sample calculations using 245GHz. Today, 95GHz beams are used in tactical weapons, with power levels adjustable down to the levels needed for non-lethal crowd control. The choice of frequency is thus a tradeoff between antenna size to capture a given percentage of the beam power, and the losses due to atmospheric absorption. This trade is skewed towards low frequencies, for a fixed-location system such as a GEO-to-equatorial surface link, where rain and cloud cover affect the reliability of the system. However, for a dynamic space power grid, with numerous options for getting power to a given location, the atmospheric loss problem is secondary. Hence the choice of the 200MHz regime for the baseline system. This also avoids overlap with commonly used communication frequencies. We will use 200MHz for conservative sizing, and leave the precise choice above 200MHz to system designers.

If technologies arrive for converting power at one frequency to power at a vastly different frequency, with near-100% efficiency, then the atmospheric transmission should occur at a low frequency while the long-distance satellite-to-satellite transmissions should occur at high frequency (200GHz regime). Today we have no indication that this is viable.

Internal Rate of Return

The Internal Rate of Return (IRR) selected for this enterprise is a low 8%. This is because it is anticipated to be funded by an International Space Infrastructure Consortium[4]. The reasons why large space infrastructure is best implemented using such a consortium are discussed there. In our system, certain parts of the SPG will indeed be far more profitable than others (Bekey et al considered a segment with a 35% IRR); however, limiting participation to those markets will not permit expansion through the subsequent phases.

Sizing satellites

As discussed below, the choice of orbit height and frequency dictate antenna size. Antenna size influences satellite mass and launcher size, but it also determines the smallest retail customers who can receive beamed power directly from the SPG. By going to the 200MHz range, the SPG opens up to a very large number of customers in the long run. Table 1 shows some consequences of the choice of beaming frequency. The minimum antenna size at 2.45 and 10 MHz is quite large, implying a large launch cost penalty, and cutting the number of viable ground locations. The ground transmitter diameter choice for the 200MHz case is based on beam intensity, as discussed later.

Table 1: Antenna Sizing Considerations

Frequency (GHz)	2.45	10	200
Wavelength(mm)	120	30	1.5
Ground to Satellite			
Receiver diameter on sat, m	300	300	50
Orbit height (km)	800	1100	800
Design transmisssion distance (45-deg), km	1131	1556	1131
Diameter of transmitter on the ground (m) calculated	1127	380	83
Efficiency of beam capture	0.99	0.99	0.99
Actual diameter of transmitter on ground	1200	3000	500
Satellite to Satellite			
Distance between sats (km)	2400	2400	2400
Antenna diameter, m	846	419	94

ARCHITECTURE

Number of ground stations

The initial number of ground stations that must participate to ensure continuous power beaming, is determined by the cone angle within which a ground station can reach a satellite. This depends on the range of the phased arrays used to direct the beamed power. We assume that a cone of half-angle 45 degrees is accessible, i.e., 90 degrees of sky is visible, and accessible to the phased array transmitter. Beaming distance for antenna sizing is figured at 45 degree beam angle. In the initial phase of the SPG, 36 satellites are placed in low earth orbits over 10 years, as 100 plants come on line ("on beam" to be precise). These satellites must be distributed between sun-synchronous[27] (near polar) orbits at roughly 800 km, and some near-equatorial orbits. The orbits can be optimized to provide better coverage for provider plants and receivers at their respective peak hours. With 72 to 96 satellites, the SPG will be able to provide complete global coverage in 20 years, with 268 plants, keeping the demand factor around 50%. Table 2 shows some architecture decisions.

Table 2: Independent Variables

Parameter	Baseline	Why
Orbit height above surface	600km	Launch cost and antenna size
Atmospheric transmission frequency	200-245 GHz	Reduce antenna sizes, avoid water bands
Internal Rate of Return	8%	Infrastructure Consortium
Phase Array transmission	45 deg. half-angle	Cover 90 degree azimuth of sky
Initial number of ground stations	100	Revenue generation rate
Initial number of satellites	36	Near-continuous beaming

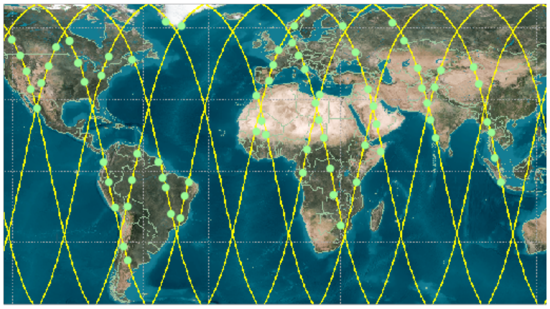


Figure 2: Daily orbits of a sun-synchronous satellite, with power plants imagined along certain orbits.

Orbit Optimization Problem

Few if any power plants will be built solely to transmit through the Space Power Grid. Fifty to 75% of output will use terrestrial lines to serve their local market. However, SPG makes the difference in enabling them to achieve large capacity, and to achieve baseload status. Satellites should pass directly above transmitting locations to minimize atmospheric transmission loss at the highest power levels. Precise passes must occur over solar plants during peak sunlight, and over nuclear plants at night.

Figure 2 illustrates the possibilities with sun-synchronous satellites. It shows the daily orbits of a sun-synchronous satellite 888km above earth. For illustration, imaginary locations of power plants are indicated along the arms of one orbit. A single orbit covers several interesting regions capable of hosting different kinds of power plants, from nuclear and hydroelectric plants in North America, to solar plants in north Africa, and wind plants in Greenland. Not all will be beaming at a given time – some will be receivers while others will be beaming power.

Ground stations to generate and beam microwaves will be located in dry high-desert locations at lower latitudes where land is cheap and sunlight abundant, with few cloudy days per year, and mountainous / coastal ridge regions with high winds. Obvious locations are the high plateaux of New Mexico, Afghanistan, the Andes, Tibet, the Gobi, Thar, Sahara, Kalahari, Australian, and Californian deserts. Wind energy plants at high latitudes, such as in the Dakotas, Canada, the glaciers of Greenland and Antarctica, are also good candidates. Sea-level plants will benefit from the Space Power Grid because the cost of laying transmission lines is traded off against the lower efficiency but quicker access to the SPG, and hence a quicker amortization period. Receivers can be located anywhere, but note that in the near term, the SPG is an augmentor, not a baseload supplier, for retail delivery. Larger receiver stations will be positioned to receive from any of several satellites, and hence get 24-hour coverage.

In the interests of conciseness, we leave this optimization problem to later work, and present bounding values. With a 90 degree phased-array beaming cone, a given station must be able to reach a new satellite once every 15 minutes, under worst-case conditions for continuous coverage. This indicates that a constellation of 96 satellites will suffice. Partial coverage operations can commence with as few as 36 satellites.

Satellite-satellite beaming

This step can conceptually be achieved with minimal losses, if the antennae can be designed to accommodate at least 99% of a Gaussian beam. Also, the redirection and distribution of incoming power to these re-transmitters can be done using high-efficiency waveguides. The satellite-satellite beam must travel 2400 km in many cases, and thus dictates the use of high frequencies.

BASELINE SYSTEM DESCRIPTION

Phase 1: SPG

1. SPG Transmission Satellites

Thirty-six microwave reflector antenna satellites, sized to handle a 250MW peak load, will be distributed in earth orbit between sun-synchronous (nominal 888km) and equatorial circular orbits. Each satellite will have thin-film/ fine-grid adaptive antennae, with computing and micro thrusters to point and shape the antennae as needed. Each will have the capability to redirect an incoming microwave beam (nominally 200 - 245 GHz) to 4 other satellites, and 100 retail earth receivers.

2. Thermal Protection, Storage and Regeneration

Clearly the heat load on the satellite from the power throughput is greater than can be handled by a passive radiator. We propose a closed-loop helium/xenon gas heat exchanger to remove heat from the highest-temperature portions of the system. The hot gases drive a turbopump. This system exchanges heat with an oil-salt mixture, which also provides stability during power fluctuations. The turbopump provides on-board power, and pressurizes the Xenon propellant for the orbit correction system. However, the power available is far more than that necessary for these tasks. It is possible that the excess power can be used to beam power to Space-based customers. In this case, two options open up. The liquid system provides a way to store a small percentage of the energy for short durations. The independent generator provides a way to beam frequencies different from those used by the main grid. These aspects remain to be explored.

The mass of the TPS (minus any beamed electric generator) can be estimated crudely using thrust-to-weight ratios achieved by modern-day fighter jet engines, which produce roughly 100 to 125 MW. This shows that such a system can be confidently built under a mass of 2000kg. While substantial, this is not a show-stopper.

One system can provide a constant power supply by utilizing LiF TES energy storage canisters by storing and releasing energy through the LiF heat of fusion during hot and cold cycles respectively, and then transferring throughout the cycle by Xe gas[28].

In Table 3, the baseline system characteristics are laid out. Satellite mass is estimated using published values for antenna size and cooling system masses, with liberal allowances. At this stage the issue is to see what system size is needed to become economically viable. The total cooling system mass is set at 2000 kg. The Phase 1 SPG satellite mass is set at 5000kg.

The beam intensity at the ground is several times the U.S. Federal standards for human exposure; however, unlike the Japanese demonstration concept, this power is not illuminating a general area, and is above a transmitter array at a controlled-access power plant. The ground array size of 500m diameter, can be increased substantially at most remote locations, if dictated by local regulations. The beam power level at aircraft altitudes is high, and the sweeping beam poses problems within a cone expanding from the ground transmitter. We anticipate that areas in this vicinity will be no-fly zones – a concept that is far easier to rationalize today than it was a few years ago. In all cases, beam interruption would trigger automatic shutoff as standard practice. Intensity at the satellite antenna is obviously very high and requires active cooling.

Table 3: System Characteristics

Power transmitted (design, MW)	250
Average beam intensity, uniform, at ground, w/m^2	1273
Average beam intensity, uniform, at satellite, w/m^2	127323
Antenna mass, kg	38.9
Mass for space-space antennae, kg	546
Cooling system mass: 2000kg/2.5MW	2000
Mass of fluid, for 400K heating in 60 seconds at 2.5MW, kg	400
Other systems	1000
With margin of 1000 kg, total satellite mass, kg	5000

PHASE 2: AUGMENTATION

After 20 years, the satellites will be upgraded with ones carrying solar collectors and over-sized converters to generate microwave power from sunlight. Several technologies currently under development may mature enough to use in this phase. One direct conversion technology is to use optical antennae to capture sunlight directly with very high efficiency, and convert to microwaves. A different option is some form of integrated solar maser/laser. Either of these would enable reduction of the converter mass, and improvement of its efficiency. The key feature, however, is that the converters are located at 800km orbits rather than GEO, thereby greatly reducing the cost of launching and refurbishment.

In the baseline case, if none of them matures, we propose to use a large ultralight collector (assumed 300m diameter) to focus sunlight onto high-temperature solar cells, and then convert this to microwave. However, the high-temperature cell array will be sized to take 100 times as much solar energy as can be captured by the collector. This phase will contribute only a miniscule amount to the power grid – roughly 18 - 36MW from each satellite. However, the marginal cost of generation of this power is low, and it gets delivered with higher efficiency. The gross profit from this power is roughly $6M per year per satellite.

The Augmented SPG satellites of Phase 2 are assumed to have 7000kg mass due to the addition of the collector/converter, and upgrading their throughput, cooling and transmitters (to the ground) to handle 100 times the power of the initial SPG. Their launch cost is taken as $42M, and the development cost at $42M, so that total outlay per satellite is $84M. Over their 20-year projected lifetime, power generation adds $120M to the revenue stream, so it is clear that these will pay for themselves when the baseline transaction business is added. By Year 30, all 96 Augmented SPG satellites should be in place, ready to handle the massive power stream from the full SSP phase. They will have added only 8.2% power to the SPG phase.

Why not use A-SPG sats in Phase 1? The answer is that the collector/converters are bound to be much more efficient, and have less mass and launch cost, 20 years from now.

Phase 3: Baseline Space Solar Power

Large ultralight concentrator / reflectors will be placed in high orbits to direct sunlight directly to use the full capacity of the collectors on the Grid spacecraft. Assuming 3km diameter collectors, this means a factor of 100 increase in the power collected from Space. In addition, these would be available to all 96 SPG satellites. Thus from Year 31 to Year 40, deployment of the 96 SSP collectors will occur, adding 7.69 million GWh to the SPG level. This is 64 times the power that was handled by the SPG phase, but the addition is to the distributors, not to the 250MW antennae. It is not clear if the 96 satellites of the Augmented system can handle this much power, or whether more relay satellites must be added.

Phase 4: Expansion of Space Solar Power

In this phase, another 5-fold expansion of the solar power system would be needed, to realize the potential of space solar power to reach at least 5000GW, 24-hour power plant output. Thus the full SSP system by this approach may consist of 500 3km diameter collectors at high orbits of perhaps 10,000km, and 500 to 1000 Power Grid satellites distributing to retail stations on the ground.

The key point still remains: What is placed in high orbit (probably much lower than GEO) will still be ultralight collectors, not massive converters.

ARCHITECTURE OPTIONS

In the Space Power Grid phase (Table 1) there are two types of satellite designs: The first is a constellation of distribution satellites, which receive power from the ground and/or other satellites, and send it to other satellites or to receivers on the ground. As these age and are replaced, the next generation of satellites in the Augmented SPG Phase will have a solar collector/converters integrated. At minimum, these will be arrays of solar cells tuned to certain wavelengths, so that they have high conversion efficiencies to microwave power from sunlight in those ranges, without the attendant heat rejection problem of broad-band cells. This would add a small amount of power to the grid.

There are 4 possible options for adding more power to the grid, depending on how technology advances:

a. Use conventional photovoltaics on the LEO satellites, perhaps with large-area collectors attached to them. The collection efficiency would be lower than with GEO satellites that can receive power continuously, but this has the advantage of having the ground infrastructure already in place for synchronized beaming.

Table 4: Architecture Options for the Different Phases				
	Satellite Orbit	Transmission Frequency	Transmission Target	Receiving Frequency
Space Power Grid Phase (GND->LEO->LEO->GROUND)				
1. Distribution Satellite	LEO	Microwave	Ground/LEO	Microwave
2. Distribution Satellite + tuned solar cells	LEO	Microwave	Ground/LEO	Microwave+Narrowband Optical
Space Solar Power Phase (GEO/SUN->LEO)				
3. Conventional Photovoltaics	LEO	Microwave/Narrowband Optical	LEO - 1 or 2	Sunlight
4. Solar Pumped Laser	LEO	Narrowband Optical	LEO - 2	Sunlight
5. Solar Pumped Maser	LEO	Microwave	LEO - 1	Sunlight
6. Optical Rectenna + Direct Conversion	LEO	Microwave/Narrowband Optical	LEO - 1 or 2	Sunlight
Full Space Solar Power (SUN->GEO->LEO)				
7. Sun Sats - Reflector	GEO	Reflected Sunlight	LEO SSP Sats (3-6)	Sunlight

b. **Use direct solar conversion to lasers**, laser transmission between satellites, but convert to microwave to beam to earth. Recently, JAXA has shown Nd-Cd-fiber lasers up to 38% efficient in converting broadband solar spectrum energy to 1054nm beams[29]. These satellites would receive incoming laser energy using their high-efficiency narrow-band photovoltaic cells, convert it to microwave, and beam it to Earth. This architecture has two advantages: the beaming to Earth could be done at optimal microwave frequencies for maximum transmission through the atmosphere, with small transmitter size. The laser beams would propagate with very high efficiency, and require only small collectors. Thus the mass and overall cost per unit power of the system with this architecture may be substantially lower than the lower-risk option presented before.

c. Solar-pumped MASER that produces microwave beams directly from broadband sunlight. While direct-solar-pumped Masers were investigated in the 1960s, and moderate efficiencies were shown, little work has been found on this topic recently. Given the new developments in direct solar-pumped lasers, the question is worth reopening. Issues of shifting frequency to sub-harmonics must be resolved. Should this become feasible at high conversion efficiency, the system mass per unit power can be brought down considerably.

d. Direct conversion from sunlight to beamed microwave using an optical rectenna.
An optical rectenna is a device that has antenna elements built to receive the shortest wavelengths of interest in sunlight, and has enough of them spaced over a large area to be able to also tune in to the largest wavelengths of interest. The basic issue in making such rectennae is to develop fabrication techniques that can handle the nanometer-scale resolution needed for the energetic frequencies of sunlight. In theory, should this work, extremely high efficiency conversion can be achieved, and the system mass can be quite small.

The kick-start for Space Solar Power comes from the proliferation of earth-based transmitter/receiver/distribution infrastructure compatible with future solar-power satellites. We project that Direct Solar Conversion to microwave beams will become feasible with a 50% efficiency and reduced mass by 2035. The frequency tradeoff is between the regime below 10 GHZ, and the regime around 200-250 GHz, as discussed before.

TECHNOLOGY OPTIONS

Benford[30] describes microwave sail material and construction. An ultra light carbon sail of mass density 5-10g/m^2 with a carbon-carbon micro truss was used with 7.16GHz microwave beams. However, these absorbed up to 10% of the incident intensity, and got heated to high temperatures. Deployment of such sails by absorption-induced spin has been addressed.

Direct conversion from broadband sunlight to microwaves is a goal with tremendous technological implications. The numbers are significant. Today, one has the choice of using photovoltaic conversion to direct current (DC) with a limiting efficiency under 50% and then to the preferred microwave frequency, with an efficiency of perhaps 90%.

Overall limiting efficiency is thus around 45%, from sunlight to beamed power. Realistic system efficiency[12] is on the order of 16%. A much worse problem is the mass of the power conversion equipment, which works out to roughly 1kg per kilowatt. Direct conversion devices (DCD) promise efficiencies of up to 85% in converting to DC, but even more exciting is the prospect of 85% efficiency to microwaves, without the massive conversion equipment. The key to this technology is in constructing antennae with mesh dimensions comparable to the wavelength of visible light. This pushes nano-fabrication technology. We expect to see rapid progress in this field in the coming decade.

Currently, work on Optical Rectennae aims to convert sunlight to direct current using antennae with nanometer-scale etchings. Work on Schottky diodes aims to boost the efficiency and bring down the mass of DC to microwave conversion. Berland et al give a recent status report[31,32]. Kellum[12] projects 50% system efficiency, enabling 67% mass reduction for the same power compared to PV systems.

Much of the technology items in SPG can be developed on earth, with little formal R&D needed in orbit. Microwave reception and reflection in high orbit has been used since the days of NRL's 6-ton GEO craft of the 1970s, which listened to transmissions between microwave towers in the Soviet Union. Beam propagation through the atmosphere has been amply tested, and retro-guided high-power beam locking on spacecraft is a basic part of Space Defense technology. Ground-based telescopes and GPS receivers track LEO satellites routinely. Deployment of ultra thin antennae/ sails/ reflectors is being studied at JPL.

Momentum Vector Scheduling

The active heat transfer systems of the SPG have the power, and the supplies of propellant, to perform emergency station-keeping. Over time, the power beams can provide some appreciable thrust. Some thought has to be given to momentum-vector-scheduling power beam transfers in different directions for each craft, depending on its needs for orbital velocity vector changes. The impact here is that propellant mass no longer dictates system life. The life of the low mass antennae and switching electronics and power storage systems may be the limiting factors, other than the risk of micrometeoroid or space junk impact.

END-TO-END EFFICIENCY

Table 5 compares the best that can be done today in terrestrial power generation with what can be done in the shorter term with the SPG, the intermediate term with direct conversion augmented SPG, and finally with full SSP.

Table 5: End-to-End Efficiency Comparison

	Conventional power	SPG	A-SPG	Full SSP
Conversion from source	0.4	0.4	0.5	0.99
To transmission mode	1.0	0.7	1	0.5
Atmospheric traverse		0.9x0.9	0.9	0.9
In-space transmission		0.98	0.98	0.98
Delivery to user	0.94	0.9	0.9	0.9
End-to-End	0.376	0.200	0.397	0.393

Thus, in the short term, SPG is only 53% as good as terrestrial power generation. In the longer term, with direct conversion to microwave from broad-band solar, it gets better than terrestrial. We note here that Henley et al[33] project combined system efficiencies for radio-wave wireless power transmission, in the range of 60 to 70%.

In discussing the business case, we show why the low efficiency at the SPG phase is not a killer objection. The SPG opens up markets where these efficiencies are still acceptable.

BABY STEPS TOWARDS SPG

The 4-step approach outlined above provides an evolutionary path, with revenue generation starting early. However, even this involves a multibillion dollar global investment, and thus poses large risk. To reduce these risks, a low-level process is suggested below:

- Low-altitude beamed-energy exchangers. A short-term demonstration of the merits of beamed power would consist of transmission over a mountain range, or across a small body of water. The first stage might be a pair of energy relay stations on a mountain range, taking power beamed from one side and delivering it to ground stations on the other side. This is a small step, not much beyond what was demonstrated many decades ago by W.C. Brown[34].

- A long-endurance aircraft might constitute the "reflector" in the next case (transmission across a body of water or larger distance), and it is possible that its engines could run on the waste heat from power transmission.

- A new DARPA initiative aims to deploy large balloons at altitudes high enough to qualify as the "edge of space". This is an obvious platform to demonstrate SPG steps.

BUSINESS CASE

Parameters for Phase 1 Business Case

Table 6 lists the parameters used for the Phase 1 business case calculation. It is assumed that only 30% of the power that is sent to the microwave converter/beaming system actually reaches the customer as useful electric power. The development cost of the spaceand ground portions for the first 36 satellites, and the first 100 stations is expended over the first five years of the enterprise. The first two satellites are launched in Year 6, with 10 ground stations participating, and generating revenue. Each ground station is assumed to beam up 100MW with a 50% operations factor (i.e., they beam up on average, 100MW for 12 hours a day, 365 hours a year, and none the rest of the time).

The issue here is to see at what cost of power, the system can break even (reach positive Net Present Value) within 20 years. The answer from Figure 3 is roughly a production cost of power of \$0.04 per raw unit of power generated, and a selling price of \$0.20 per unit of power actually delivered at the customer's receiving site. This is because of the 30% efficiency of the conversion/ transmission/ reception/ reconversion process. This is conservative compared to what is laid out in Table 5, where the product of the efficiencies excluding the basic power generation, works out to 0.5 for the Phase 1 SPG. We leave the economics calculation at the conservative 0.3 level. The 0.20 per delivered KWh selling price is quite reasonable for many parts of the world which do not have access to the established high-voltage transmission lines and paid-off nuclear plants of the USA.

Table 6: Enterprise Business Case: Phase 1 Parameters

Launch cost at \$6K/kg to 880km, \$M	30
Per satellite cost for one of the first 36, \$M	30
Operations cost per satellite per year, \$M	5
Satellite system development cost, \$M	1000
Ground facilities development cost for 1^{st} 100 stations	1000
Connection cost per additional station, \$M	25
Cost of production of power, \$/KWh	0.04
Fraction received as useful electric power	0.3
Sales price, \$ per KWh	0.2
Gross profit per KWh	0.02
Beamed average MW per plant	100
MWh per year, for 1 plant at 50% duty cycle, per satellite available (100%=36sats)	12175

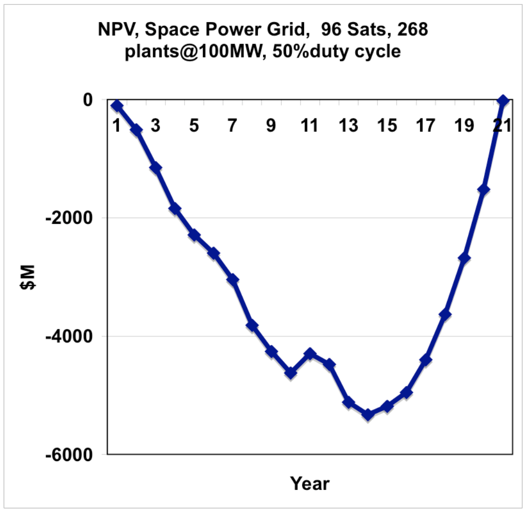


Figure 3: Net Present Value, with 96 satellites and 268 plants in 20 years.

In Figure 3, an inflection point appears at Year 10. This is the end of the depoyment of the first 36 satellites. An interval of two years is introduced before the start of Phase satellite launches, simply to illustrate that with the 36-satellite system, the NPV curve has turned upwards as soon as deployment is completed. Clearly, the 36 satellite system will break even in a few more years. Satellite life is designed for 20 years, so that delaying expansion of the system may recover much of the investment. We start system expansion in order to get to the full SSP Phase quickly. The deployment of the Augmented satellites could also be sped up, but at the cost of deeper dip in the NPV.

Figure 3 shows that the full 96-satellite system will come to positive NPV in just over 20 years. The development and launch costs of the Augmented satellites is large, and should be funded at that stage on the basis of the proven capabilities of the SPG system. While the added power generation due to these satellites is small, it does pay off the added cost of the augmentation over the next several years. We do not stretch out the NPV curve to show this, in the interests of clarity. The space power added to the Augmented satellites, costs much less (essentially nothing beyond the installation), and is more efficient because it is available in Space in full, ready for distribution with just one atmospheric pass. Thus the profit per KWh from this power is substantial even with the reduced sales price of $0.15 per KWh for this part, and it can now compete in markets where power cost is lower. This permits further market expansion. Parameters for Phase 2 are shown in Table 7.

Table 7: Parameters for Phase 2 AugmentedSPG

Collector/Converter Diameter, m	300
Area, sq.m	70686
Satellite Mass: Add 2000kg	7000
Per satellite cost, $M	42
Launch cost @$6000/kg, $M	42
Solar conversion efficiency	0.25
KWh per year per ASPG sat, at 50% duty cycle	100,621,000
End-to-end efficiency	0.4
Cost of production	0
Sales price, $per KWh, Phase 2	0.15
Gross profit per KWh	0.06
Gross profit per year per Augsat, $M	6.04

It is easier to see that the full SSP phase generates large positive revenue, since the power added, per dollar spent on installation in orbit, is substantial, and again this power comes at zero cost once installed. Parameters for Phase 3 are shown in Table 8. Launch cost per kg is higher since the collectors are to be deployed at an altitude of several thousand kilometers. This altitude is high enough that each collector can see the Sun 24 hours a day, so that the power beaming to the Augmented satellites below, is continuous, day and night. By this stage of development, Earth-based "Green" plants enabled by the SPG are expected to be paid off, so that the selling price of power can come down, and markets expand again. As conversion efficiencies from sunlight to microwave, and from microwave to useful devices, increases, the cost will drop further. We do not try to present NPV calculations for these phases, since they will appear to be wildly optimistic at this stage, and anyway they refer to markets 30 to 40 years from now.

The drop in prices of power due to full SSP is not expected to destroy the "Green" plants, since these plants can now get plenty of power from Space, cheap to keep them at baseload levels. However, it can be seen that there may not be much incentive for new plants to be built on Earth once full SSP comes into the market.

Table 8: Parameters for Phase 3, Full SSP

Collector Diameter, m	3000
Area, sq.m	7.06E+06
Satellite Mass: 0.015kg/m^2	106029
Per satellite cost, $M	100
Launch cost @$10000/kg, $M	1060
Solar collector efficiency	0.995
KWh per year per SSP sat, at 100% duty cycle	80E+09
End-to-end efficiency	0.4
Cost of production	0
Sales price, $per KWh, Phase 2	0.15
Gross profit per KWh	0.06
Gross profit per year per Augsat, $M	4806
Total KWh per year added by 96 sats	7.69E+12

DISCUSSION

In the earlier version of our SPG concept design, shown in Boechler et al[35], the baseline SPG satellite system was sized to recover 50% of system deployment cost in 20 years from savings in costs of ground transmission, based on current cost of long-term debt. The cost per SPG satellite was projected to be lower than the cost of a replacement GPS satellite ($44M), and the launch cost was lower. Thus the cost to first revenue generation was on the order of 2 Billion dollars, compared to the $300B for current SSP concepts. The basic cost of delivered power from SPG is roughly twice that of US domestic power cost at the beginning, since the efficiency is only about half as much (0.2 vs. 0.376). However, there are several advantages that make SPG power viable even at these costs. As mentioned before, these include:

1. Use excess power from the spikes in generation at “green” plants (wind, solar, hydro-electric).
2. Delivery to peak-demand locations (greater revenue). Landis[36] shows, for instance, that during a typical summer day in New York City, the price of power fluctuates between \$0.06 and \$.40 per kilowatt-hour.
3. Access to markets with much higher present-day costs than the contiguous US.
4. The market for beamed power in Space. The prices in Space are bound to be far higher than those on Earth, so that this is likely to be a lucrative market. Benford[26] indicates that being able to beam 10KW to a satellite would save on the order of \$100M off the cost of the satellite.

One key result in this paper is that the initial SPG can break even within ten years or so of first launch. This assumes a low cost of power production, at \$0.04 per KWh. This appears to be low, until one takes into account the opportunities from the Carbon credits and replacing fossil fueled plants. Clearly, some measure of public support may be assumed for this phase. Equally, the development costs for the SPG, and its insurance costs, may be assumed to be borne to some extent by public funding, until the system is established. This is reasonable based on the history of the Global Positioning System, and its new European competitor, the Galileo system.

Beyond the first phase, the system shows every sign of being self-supporting, on the prospects for full SSP. Again, once the augmented satellites are launched, there is no reason to delay launch of the full SSP collector satellites, as shown here. Thus, Phases 2 and 3 may be integrated, if funding streams are available.

This approach does assume a good deal about the technologies and efficiencies for generating microwaves at high power in the 200MHz regime, of pointing and tracking satellite antennae and ground antennae, and of positioning and tracking large ultralight collector arrays. There is technology for each of these; however, their adaptation to this problem, and their integration, will no doubt pose interesting challenges.

CONCLUSIONS

Breakthroughs in direct conversion from broadband sunlight to beamed microwaves and lasers, merit a re-examination of the dream of Space Solar Power. This paper lays out one path to develop SSP in an evolutionary manner, with revenue generation starting at a very low level of investment, and going all the way to doubling total global power generation and beyond. The Space Power Grid will start with an energy transaction business, using microwave beaming, reception and waveguide technology. In the next stage, direct conversion will augment power generation into an established infrastructure. In the final stage, sunlight collected over large areas in middle-level orbits will be focused onto the converters on the LEO craft, to deliver full-scale space solar power. In the long term, this can be achieved with better efficiency than the best of present-day terrestrial power generation.

Specific results show that:

1. The initial stage Space Power Grid breaks even on an investment on the order of \$4B, with 36 satellites and 100 ground stations, in roughly 10 to 15 years after project initiation. The low production cost assumed for this phase requires support from the carbon credits and fossil fuel replacement programs.
2. The extended form of the Space Power Grid breaks even, with an investment of \$6B, 96 satellites and 268 ground stations, within 21 years.
3. Once the system is refurbished with Augmented satellites and collectors in high orbits, power costs are expected to drop, and profits rise sharply. These steps appear to be achievable using the revenue streams from the initial Space Power Grid.
4. This system shows how the launch cost problem to geosynchronous earth orbit can be avoided, and a full Space Solar Power system and its ground infrastructure set up within 40 years, at a manageable and recoverable cost.

ACKNOWLEDGMENT

The second author was supported through a National Student Fellowship by the NASA Institute of Advanced Concepts. The first author gratefully acknowledges support from the NIAC through a Phase 2 grant, and the MacArthur Foundation through a Sam Nunn Senior Security Fellow appointment at the School of International Affairs, Georgia Institute of Technology, and valuable discussions at the Colorado School of Mines.

REFERENCES

---

[1] Glaser, P.E., “Power from the Sun:It’s Future”. Science, Vol. 162, p.957-961, 1968.

[2] Mankins, J.C., "A Fresh Look at Space Solar Power", 38th IAF Federation conference (1997);

---

[3] Landis, G., “Evolutionary Path to SPS”. Space Power, Vol.9, No.4, 365-371, 1990.

[4] Komerath, N., Nally, J., Tang, E., “Policy Model for Space Economy Infrastructure”. IAC2005-D3.1.08, IAF Conference, Fukuoka, Japan, October 2005.

[5] Landis, G., “Reinventing the Solar Power Satellite”, NASA TM 2004-212743. IAC-02R.3.06, February 2004

[6] Bekey, I, Boudreault, R., “An Economically Viable Space Power Relay System”, Acta Astronautica, Vol. 44, Nos. 7-12, pp.385-390, 1999.

[7] Fairley, P., “Steady As She Blows”. IEEE Spectrum, August 2003, p. 36-39.

[8] US Department of Energy, Energy Information Administration, “World Energy Overview: 1994-2004”, International Energy Annual 2004, report released May-July 2006. Viewed Sep. 10, 2006.

[9] NASA, Sep. 19-20 1995, " Space Solar Power, An Advanced Concepts Study Project", NASA HQ, NASA LeRC SSP Technical Interchange Meeting,", Washington, D.C. 1995.

[10] "Laying the Foundation for Space Solar Power” (2001) – NRC http://www.nap.edu/execsumm/0309075971.html.

[11] “Introduction to Part III – The Keys to SSP.”. http://www.sspi.gatech.edu/

[12] Kellum, M., Laubscher, B., “Solar Power Satellite Systems With a Space Elevator”. LAUR-04-4073. 3rd Annual International Space Elevator Conference, Washington, D.C., 29 June2004

[13] Criswell, D.R., “Lunar Space Power System for Energy Prosperity Within the 21st Century”. http://www.worldenergy.org/wec-geis/publications/default/tech_papers/17th_congress/4_1_33.asp

[14] “The Consumer Impact of Global Warming Policies: Consumer Alert, Jan2000 http://www.globalwarming.org/

[15] Adler, C., “Turning Point: A South Dakota tribe’s utility rides the wind..”. Fortune Small Business, Feb. 05, p. 47.

[16] Bekey, I, Boudreault, R., “An Economically Viable Space Power Relay System”, Acta Astronautica, Vol. 44, Nos. 7-12, pp.385-390, 1999.

[17] Nagatomo, M., Itoh, K., “An evolutionary satellite power system for International demonstration in developing nations”. Proceedings of SPS91, pp 356-363. Also at http://www.spacefuture.com/archive/an_evolutionary_satellite_power_system_for_international_demonstration_in_developing_nations.shtml Viewed Sep. 12, 2006.

[18] Y Kuroda, M Nagatomo & P Collins, "Japanese Perspective on Power from Space for Earth", SPS Rio 92 - Space Power Systems and Environment in the 21st Century Symposium, SEE, Paris, 1992. http://www.spacefuture.com/archive/japanese perspective_on_power_from_space_for_earth.shtml Viewed Sep. 12, 2006

[19] Anon, “SPS2000: An SPS pilot plant project”. Glossary of Terms – SPS 2000. http://www.spacefuture.com/cgi/glossary.cgi?gl=term&term=SPS%202000 . Viewed Sep. 12, 2006

[20] Nagatomo, M., “An Approach to Develop Space Solar Power as a New Energy System for Develop Countries”. Solar Energy, Vol. 56, No 1, pp 111-118. Also at http://www.spacefuture.com/archive/an_approach_to_develop_space_solar_power_as_a_new_energy_system_for_developing_countries.shtml Viewed Sep. 12, 2006.

[21] Brown, W.C., “Performance Characteristics of the Thin-Film, Etched-Circuit Rectenna”. 1984 IEEE MTT-S DIGEST, pp. 365-368, 1984.

[22] Shaposhnikov, S.S., “Wireless Power Transmission Antenna Peculiarities for the Space Power Systems”. At www.sspi.gatech.edu/antenna.pdf Viewed Sep. 14, 2006

[23] Cooper, M., “Antennas Get Smart”. Scientific American, July 2003, p. 49-55.

[24] Henley, M., Potter, S., Howell, J., Mankins, J., “Wireless power transmission Options for Space Solar power” IAC-02-R.4.08, 2002 Henley, M., Potter, S., Howell, J., Mankins, J., “Wireless power transmission Options for Space Solar power” IAC-02-R.4.08, 2002

[25] Sims, W.H., “High Efficiency Microwave Power Amplifier: From the Lab to Industry” . http://citeseer.ist.psu.edu/context/2121076/0 Viewed 9/14/2006.

[26] Benford, J., Dickinson, R., “Space Propulsion and Power Beaming Using Millimeter Systems”. In Intense Microwave Pulses III, H. Brandt, Ed.,SPIE 2557, 179 (1995). Also published in Space Energy and Transportation, 1, 211 (1996).

[27] Anon, “Satellite Coverages and Orbits”. http://www.rap.ucar.edu/~djohnson/satellite/coverage.html#polar Viewed Sep. 10, 2006

[28] Wichner, R.P, Solomon, A.D., Drake, J.B., Williams, P.T. Thermal Analysis of Heat Storage Canisters for Solar Dynamic, Space Power System.

Oak Ridge National Laboratory. Martin Marietta. April 1998.

[29] Saiki, T., Motokoshi, S., "Development of Solar-Pumped Lasers for Space Solar Power". IAC-05-C3.4-D2.8.09, 56th International Astronautical Congress, Fukuoka, Japan, October 2005.

[30] Benford, J., "Flight and Spin of Microwave-Driven Sails: First Experiments".

[31] Berland, B., Simpson, L., Buebel, G., Collins, T., Lanning, B., "Optical Rectenna for Direct Conversion of Sunlight to Electricity". ITN Energy Systems, CO.

[32] Berland, B., "PhotoVoltaic Technologies Beyond the Horizon: Optical Rectenna Solar Cell". Final Report, NREL/SR-520-33263, February 2003.

[33] Henley, M., Potter, S., Howell, J., Mankins, J., "Wireless power transmission Options for Space Solar power" IAC-02-R.4.08, 2002.

[34] Brown, W.C., "The History of Power Transmission By Radio Waves". IEEE Trans.Vol. MTT-32, p:1230 (1984)

[35] Boechler, N., Hameer, S., Wanis, S., Komerath, N., "Evolutionary Path towards Space Solar Power". Proceedings of STAIF 2006, February 2006.

[36] Landis, G., "Reinventing the Solar Power Satellite", NASA TM 2004-212743. IAC-02R.3.06, February 2004