An Evolutionary Model for Space Solar Power

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Abstract. The primary difficulties with the dream of Space Solar Power (SSP) for Earth, are the extreme launch costs of solar power satellites to Geosynchronous Earth Orbit (GEO), and the absence of an evolutionary path to SSP. This makes the cost-to-first-power unacceptably high. This paper presents a 3-stage approach to SSP, and lay out the problems and opportunities. The key idea is to use space assets initially for global transmission and distribution, rather than generation, establish the infrastructure, and then add space-based power generation to a revenue-generating power grid. In the first stage, a Space Power Grid is established with satellites 1,200 km above Earth, distributing earth-generated beamed microwaves to other satellites and ground receivers. This boosts the earth-based alternative power industry (wind and solar-thermal) by providing transmission between any points on earth, and accommodating fluctuations in demand and supply. It also satisfies strategic needs for emergency power delivery. In Stage 2, direct power conversion technology will augment the existing space power grid with space-generated solar power. In Stage 3, large ultralight GEO reflectors will beam light to the direct-conversion collectors, and multiply the power through the grid. The need to put expensive, heavy solar arrays in high orbit is avoided, along with the objections to atmospheric transmission of visible light. The system would gain significantly from the development of low-mass, high-efficiency conversion equipment for direct conversion of broadband solar energy to beamed microwaves.

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INTRODUCTION

Space Solar Power (SSP) remains an unfulfilled dream for three reasons. They are the immense launch cost (Schwartz, 2001, Smith, 2003); lack of an evolutionary approach (cost to first power >$300B; McSpadden, 2002); and community opinion that local solar collection is sufficient for present needs. Given their high retail costs and unsteady nature, terrestrial solar-electric and wind power sources still remain secondary and subsidized. It discusses how to develop an evolutionary approach where revenue generation starts early. This paper serves to explain the concept and explore the major issues.

The key feature is to use the potential of the space-based infrastructure to boost terrestrial "green" energy production and thus benefit from the concerns about global warming and energy shortage. In this first paper on the concept, the scope of the project, possible benefits and the obstacles to success are considered. It is seen that the inefficiency of conversion to and from microwave poses the largest obstacle, and prevents favorable comparison with terrestrial high-voltage transmission lines. However, competitive revenue generation can come from the nonlinearity of cost with demand at various places on earth. Point delivery to small portable, mobile receivers during times of emergencies. The benefits to 'green' energy generation make the concept attractive for public support as a strategic asset. This also sets a market context for concepts to convert solar power directly to beamed energy – a prospect with many applications.

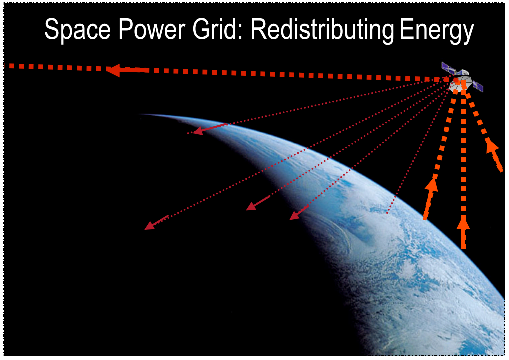

FIGURE 1. Space Power Grid Satellite.

PREVIOUS WORK

Earlier concepts used GEO PhotoVoltaic array satellites and kilometer-sized terrestrial microwave collectors. A 1995 “Fresh Look” study (Mankins, 1997) proposed more radical concepts, but the basic issue of launching the conversion equipment (1kg/kw) remained. Some have argued that pooled SSP demand for over 5000 launches to GEO would cause a collapse of launch costs. Kellum (2004) 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 (which are still to become practical). Criswell (1998) 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. Ignatiev (2000) has shown how to vacuum-deposit solar cells using lunar “rovers”, and extend this to mass-scale lunar power generation. Clearly, at today’s pace, lunar sun-power is also a distant prospect.

Concepts have been proposed for low-earth-orbit (LEO) satellites beaming power to earth, to alleviate the launch cost problem. This raises the difficulty of short, intermittent transmission and active tracking; however technological advances have made these acceptable. The shorter transmission distance (1,200km to LEO vs. 36,000 km to GEO) greatly reduces antenna size and mass. Soubel (2004) and JAXA (2004) describe a Japanese project to construct a 50KW demonstration satellite in LEO followed by a 10MW satellite in a 1,100km-high orbit, giving 200 seconds of power to ground receivers during each pass, with an orbit period of roughly 90 minutes, with retro-directive power beaming to enable tracking. This is proposed for retail power beaming to devices such as cell phones. Hoffert (2004) proposed an evolutionary technical approach to space solar power *demonstration*, stepping up through terrestrial point-to-point beaming, intermittent beaming from LEO to consumers in developing nations combined with storage devices, and beaming/reception demonstrations to high orbits using large facilities such as the Arrecibo radio telescope. The evolution here was however limited to government-funded confidence-building for full-scale SSP rather than early revenue, so that the basic SSP problem of the huge cost-to-first-power remained.

Escalating hydrocarbon costs promise to shatter community complacency and thus alleviate the third obstacle to SSP. The cost of emitting carbon is also a new factor. The net economic costs to the US from either signing, or trying to compete in a world that has signed the Kyoto Protocol, have been estimated at $160 to $260 per ton of atmospheric CO_2 released (GlobalWarming, 2000). The US DOE provides one “Green Tag” per MW (Adler, 2005) to producers of clean alternative energy, tradable on the market like the “carbon credits” of the Kyoto Protocol. House Resolution 759 proposes stringent CO_2 reductions, with further “green” credits (Gilchrist, 2005) citing penalties averaging over $15 per ton of CO_2. Northwestern states already offer various incentives for solar energy.

Total worldwide electricity generation from 49,000 power plants is over 2,812 GW. North-American plants (4,144) average 265MW, with 774 plants producing an average 310 MW of “green” energy. Plants located elsewhere average 38MW. “Green” plants using solar and wind energy suffer from large cyclic and random fluctuations. Real-time power smoothing can turn these plants into reliable “firm sources” (Fairey, 2003), greatly increasing their value and revenue potential. Wind and solar plants are best located far away from primary consumption areas, if transmission line costs are removed from the equation. Examples are South Dakota, called the “Saudi Arabia of Wind Energy”, and Southern Nevada and the High Desert of New Mexico for sunlight. For usual power plant choices, current transmission line costs are estimated at roughly $0.02 per KWH in the U.S. Transmission loss is estimated at only 7.2% in the U.S., but is as high as 50% in many countries with old infrastructure and lower line voltages. Power costs to the consumer vary widely. In the U.S., base load costs are around $0.06 to $0.08, but in the U.K., with substantial wind and other “green” sources, the cost is as high as $0.22 per KWH. Other nations are somewhere in between. In the U.S., cost during peak demand times increases sharply. Thus the literature cites the extreme difficulty of setting up alternative-energy plants that can compete in the U.S. With our concept, U.S.- based sources could compete quite well in markets around the world.

The total solar energy falling on the projected area of the planet is roughly $1.28*10^8$ GW. Thus, doubling global energy production using renewable energy sources implies a system that captures roughly 0.002% of the total solar energy falling on earth. Very large collectors can be placed in space at GEO or beyond, without obstructing sunlight coming to earth. Thus the scope of the project is limited only by eventual concerns about handling excess heat added to Earth – when the system gets so large that solar power outside Earth’s capture area is directed into Earth.

APPROACH

We propose a space-based power transmission grid to exploit the above opportunities*, initially with no space-based generation*. The issues here are technical feasibility, end-to-end efficiency and competitiveness of cost when viewed in terms of overall economic impact. In the first stage, the aim is to create a space-based grid to handle power transactions. The competition is earth-based transmission for a new set of "green" plants all over the world, enabled in locations remote from industrial and population centers. Added impetus comes from the demonstration of national preparedness to cope with natural or other disasters. The December 2004 tsunami in Asia and the 2005 U.S. hurricane season demonstrated the vulnerability of power grids, and the opportunity for using space-based power delivery to disaster areas. This opens up an opportunity to bootstrap SSP using a national / international strategic imperative. In a second stage, to occur 10 to 15 years later, some space-generated power would be added to the satellites of the grid, with the delivery infrastructure already in place and generating revenue. It is reasonable to project that technology for direct conversion of sunlight to microwave energy will be advanced enough by then to allow much greater power per unit deployed cost than present-day solar cells. At any rate, this equipment will be in low earth orbit, not GEO. In a final stage, very large thin-film reflectors or Fresnel-lens structures will be placed in GEO to focus sunlight directly onto the converters in LEO, thus delivering large amounts of power to a scaleable infrastructure. This scheme offers a solution to the economic dilemma of local generation vs. distribution from generating hubs, by beaming energy into space from ideal collection locations, and redirecting it to earth-based microwave collectors for local distribution. It also minimizes the space-power launch cost issue by doing all collection and conversion on earth, and only reflection/ distribution in space initially.

The key enablers will be advances in ultra thin microwave receivers, "smart" digital adaptive antennae, micro thrusters, swarm guidance and navigation, power beaming and high-intensity waveguides; however in each of these areas, what we propose is no more advanced than what is being considered for other SSP approaches. The scope of the initial system is small. The initial power grid, sized to a $5B investment, leaves plenty of room for later expansion of the system to SSP. These stages in the system are illustrated in Figure 2.

Space Power Grid Phase

An initial concept is to have 36 satellites orbiting 1,215 km above earth (determined to allow line-of-sight transmission to a satellite 45 degrees away without atmospheric losses) and passing microwave beams between earth-based locations in a real-time energy trade. Each craft can handle (receive and distribute) up to 200MW at 140 GHz. Each is assumed to be able to transact power with 4 other satellites and up to 100 ground stations. The craft are sized to recover system deployment cost in 20 years from savings in costs of ground transmission, based on current GPS satellite costs (as explained below). The satellite number will rise to 72 as locations far from the equator join the system. Beaming losses to and from LEO are density-equivalent to those for 22 km of transit through sea-level atmosphere. Hence the business case applies to new plants located over 22 km from their major distribution hubs. Satellites in equatorial / tropical orbits will be capable of receiving more power from the ground, and transmitting more power to outlying satellites. Satellites in inclined orbits will distribute more than they collect from ground.

Ground stations will be located at power plants to generate and beam microwaves, at ideal solar / wind collector locations – dry high-desert locations where land is cheap and sunlight or wind abundant, and mountainous / coastal ridge regions with high winds. The US Southwest, South Dakota, Hawaiian Islands, North African, Gobi, Thar and Australian deserts and Greenland are examples envisaged. Receiving stations on the ground can be located almost anywhere. There is no need to co-locate receiving stations with generator stations. Since receivers will be much smaller in diameter than those envisaged for GEO-located SSP systems, a given utility company can place its generators at optimal generator locations, and its receivers to best distribute power to end-user customers.

The tradeoff between the choice of frequency (preferably below 10GHz to minimize atmospheric losses) and antenna size for a desired 99.93% transmission efficiency of Gaussian beams, (JAXA, 2004) poses a dilemma. The limiting transmission is between satellites (2,400 km). We choose 150m diameter antennae on the satellites as a reasonable choice for an LEO satellite to be launched on a single launcher. This means that the frequency must be at least 100GHz. We choose 140GHz in order to use calculations from the literature (Parkin, 2003). In this regime, absorption by water molecules is significant but not prohibitive, and transmission is generally above 90% (ARO, 2005). This choice will encourage location of transmitting stations in high deserts and mountainous regions, but will pose inefficiencies for delivery to places with dense cloud cover. A partial solution is to deliver power to places without cloud cover and use existing ground-based transmission lines for the remaining distance; however, this is no solution where lines are down and cloud cover persists, as in a prolonged snowstorm. Unlike the GEO SSP concepts, the LEO system can start generating revenue with roughly 20 ground-based generating stations around the equator, and 20 LEO satellites in orbits within 10 degrees of the equator. Advanced technology can be progressively incorporated into routine replacements and additions. As the earth-based transmitter/receiver/ distribution infrastructure proliferates, market size will increase.

Direct-Conversion Augmented SPG

We project that Direct Solar Conversion to microwave beams will become feasible with 50% efficiency and reduced mass by 2035. To replace current global production with solar energy at 50% efficiency, 5600 sq.km of solar collector area in space (where solar intensity is 1GW/sq.km) is required. The breakthrough needed for this is nano-fabrication technology, and the same will also permit better conversion and beaming efficiency. The SPG satellites will then be replaced with 2,000 kg–class Direct Conversion Augmented-SPG (DCA-SPG) satellites, with a 1km diameter sun-tracking ultra light collector and converter on each adding 0.5 GW to the grid. As the number of satellites increases, mean transmitting distances between satellites comes down, and hence the system efficiency could be increased by going to lower frequencies with lower atmospheric losses for the same receiver size.

Full Space Solar Power Phase

GEO sun-sats launched in the 2040s will each have 100 sq.km ultra light collector/ reflectors that simply focus sunlight onto the 1sq.km collectors of the DCA-SPG. Each is expected to add 50GW to the grid at 50% efficiency. Thus the system of 72 LEO satellites and 72 GEO ultralight mirrors, with a 70% transmission efficiency, will generate 90% of today's global energy production. It is noted here that deploying large ultra-thin collectors with high-intensity solar cell arrays is an alternative to any Direct Conversion technology, alleviating technological risk. Since the system is in LEO, the launch cost is far below that of launching solar panels to GEO.

TECHNOLOGY ISSUES

Low distributed earth orbits enable much smaller receivers on the satellites. They also permit the participation of sites at extreme latitudes with minimal atmospheric transmission penalties. The sizing of the transmitters in space is driven by the need to focus beams onto other satellite-based receivers – a 2,400 km line of sight in orbit, that will come down as the number of satellites increases. One substantial advance is in "Smart" antenna arrays (Cooper, 2003) that use digital computing to focus on thousands of individual moving cell-phone customers in real-time. One approach is to have 2km-long linear antenna arrays with up to 32,000 elements. Transmitting arrays on earth stations would be of similar dimensions, but much heavier and designed to transmit much greater power levels. Waveguides to distribute incoming power are well developed, and the power levels we propose for the initial system are easily handled by present designs for microwave guides. Atmospheric absorption is not a serious issue, and microwave conversion and beam transmission at 2.45GHz are well-understood technology (Brown, 1984). At 140 GHz, atmospheric transmission loss is on the order of 10%, for stations with dry climates, but transmission through clouds poses more serious problems. Transmission at higher frequencies offers small size and mass for the same efficiency. The tradeoff between system mass costs and the cost of atmospheric absorption and unreliability due to weather (alleviated by having multiple earth station choices separated by several kilometers) is not properly understood, since much of the high-frequency data comes from astronomical observatories until now. It is not known whether a combination of high frequencies for space-space transmission (distances of 2,000 km) and low frequencies for earth-space transmission (1,200 km) may hold advantages, with efficient conversion between frequencies on satellites. Today, such conversion is inefficient. A breakthrough is needed in this area. Likewise, the DC-microwave conversion is the limiting step in the entire process, with efficiencies limited to about 70%.

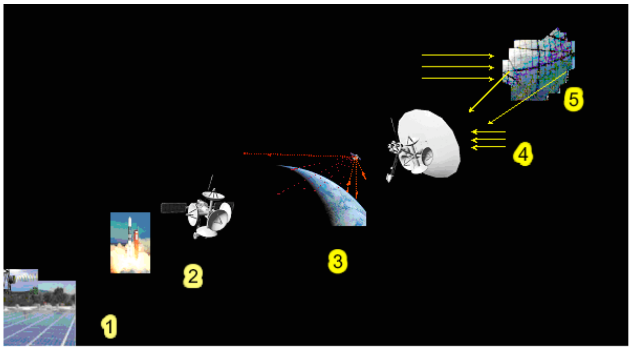

FIGURE 2. Evolutionary Path To Full Space Solar Power.
Legend:
1. Microwave Converters and Beaming Equipment Installed.
2. Thirty-Six 200-MW SPG Satellites Launched.
3. SPG in Operation.
4. Direct Converter-Augmented Satellites: DCA-SPG.
5. SSP Collector Beams Sunlight to SPG: Full Space Solar Power.

In our system, the primary power generation can come from any source, though there is not much point in using another technology that generates CO2 or nuclear waste. Current "green" options for utility-scale power generation are direct solar thermal conversion, and wind turbines. Present direct solar thermal farms heat an oil-salt mixture in arrays of long pipes placed along the focal lines of parabolic reflectors placed in east-west trenches to track the sun. The heat is transferred to run a steam turbine that generates electricity at 5 to 9 cents per KWH. Installation costs are low. With SPG, solar and wind power generation facilities can be located where they are most productive, and their power sold wherever they fetch the best prices, by beaming them through reflector satellites. Uneven generation rates are compensated by power brokering through SPG.

Heat Rejection

At the 200MW peak power level involved in the transmission through a satellite, even a 1% loss means 2 MW of heat dissipation, aggravated by the small size and mass of these satellites compared to SSP designs. However, with large thin receiver arrays attached by booms to the satellite, radiation transfer from the shadow side can suffice for thermal management. The intermittent duty cycle, as opposed to the steady heating of SSP satellites in GEO, helps in this process, but innovative means of recovering part of the power and efficiently rejecting the rest are needed. Thus, increasing the efficiency of the satellite throughput is of utmost importance. However, waveguides today have demonstrated near-100% throughput.

Direct Conversion

One key to advancing towards Space Solar Power is in using optical rectennae that convert sunlight to DC. This promises a large increase in efficiency and a large payoff from decreased converter mass from the present 1kg per kilowatt (Brown, 1984). More exciting is the prospect of converting sunlight to microwaves directly at 85% efficiency to microwaves. The technical barriers appear to be in nano-fabrication of antennae that can tune effectively to much of the solar spectrum. Rapid progress is expected in this field in the coming decade (Berland, 2003).

LEO Interference

Microwave beams pose no direct thermal threat to satellites; however, they may interfere with satellite electronics and with communications. The addition of 36 satellites will not seriously clutter LEO; however, collision with space debris is a serious risk. We have no immediate solution for this, except that the orbits are higher than most LEO 3rd-stage separation junk. The impact of Earth's magnetic field on transmissions must be considered.

TOP-LEVEL BREAKEVEN COST ESTIMATION

Several of the issues listed below are beyond the scope of this paper but may determine market feasibility.

1. Average power generation cost around the world a couple of years ago was between $0.04 and $0.08 per KWH. However, this was dominated by the low cost of hydrocarbon fuels. Hydrocarbon costs have tripled. Transmission costs are typically cited at 0.02 per KWH in the US, but may be substantially higher elsewhere

due to much higher loss percentages and land costs. Both of these costs are on the rise as "Peak Oil" appears to have been reached, and land values and environmental impact costs of power lines go up.

2. Interest rates on long-term debt fluctuate considerably.
3. The cost of carbon-based energy sources may be expected to rise further as environmental concerns impose strict limits and penalties. The global need to switch to non-hydrocarbon sources justifies some level of public (government) expenditure on infrastructure to enable 'green' power.
4. Several nations would trade their 'green credits' and buy power from nations that sell power generated through whatever means – if they could get that power.
5. At present, high efficiency is not a driving consideration in microwave power beaming, since antenna size, mass and cost are more important for transmission at low power values. A value for achievable conversion efficiency at high power level is hard to find. Most experts appear to assume a 70% practical limit using present-day technology, for open-system conversion, with 30% dissipated as heat at the conversion point. In a power plant context, it may be assumed that a good portion of this can be recovered – we assume that enough can be recovered to compensate for the 20% loss of transmission through the atmosphere and bring the loss rate to the 7 to 8% now lost in the transmission process. We expect that in future, dedicated plants to generate microwave beams can be developed to minimize the conversion loss from raw sources. Thus, the transmission approach that we propose only transmits 70% of the power generated.

The above items make it difficult to assign a value per KWH for power transacted through SPG at this stage of the concept. For simplicity, we assume that the space-based power transmission stage has a value of $0.02 per KWH transacted. To break even over the 20-year replacement period of SPG-stage satellites, the initial 36 satellites must have at least a capacity of 136MW each. This assumes that all power beaming from earth is on the sunny side (only 18 sats in view) and that each ground station has a choice of 4 satellites for its beams at any time. A market size of 5,500 GWH per year of power transmission must be achieved. This appears quite reachable for an initial consortium agreement. We project SPG launch cost of $6600 per kg to a 1,215km high orbit. Assuming satellite mass of 1,500kg, and cost per satellite of $22M, there is enough left from an initial $1.7B bond issue to fund one replacement satellite per year.

The most recent GPS satellite launches provide cost guidance on a government-developed dual-use system. The cost per 2,036kg satellite is $44M, and the launch costs $50M (or $24,557 per kg). The orbit is over 1,0000km high. The GPS model is inadequate as a reference, because of the huge user base and primary military application.

TABLE 2. Issues Comparison with Conventional SSP and Terrestrial Solar Approaches.

	SSP	**SPG**	**Terrestrial Solar**
Energy Production	Primary solar generation	Exchange; new terrestrial plants, Augmented SPG, then Full SSP	Constrained by duty cycle, & location
Launch cost	>$13,200/kg to GEO	$6,600/kg to 1215km alt. orbit	N/A.
Space Mass	>1kg/kw	<0.01kg/kw for SPG phase	N/A
Cost Items to First Power	Satellites + ground receivers	Space system + ground transmission & receiving + control.	Ground system+ line + land costs.
Duty cycle	24hr w/ reflectors	24 hr – with multiple sources	6hr/day; weather
Assembly	LEO assembly, boost to GEO	Pre-assembled – deploy in LEO.	Earth construction
Global coverage	Inclined	direct	no
Transmission losses	GEO-earth: 15% > 24,000 km space + 1 atmosphere	Conversion loss: 25%; Earth-LEO-earth: <20% Average <5,000km space + 2 atmosphere crossings.	7%
Transmission line	0	0	$2c/KWh
Breakeven	>>$1/KWH	~ 1.8 x the lowest terrestrial generation/transmission costs.	~ 2x lowest terrestrial generation/transmission costs in the U.S.

End-to-End Efficiency

At present, the end-to-end efficiency of this process alone does not compare favorably with earth-based transmission of energy, in existing markets. With 70% at conversion, and 10% for each atmospheric pass, even with essentially 100% waveguides and in-space transmission, the end-to-end efficiency is limited to roughly 50%, compared to about 90% for transmission over high-voltage lines. However, this masks the value of the approach in opening up worldwide markets, smoothing power fluctuations, avoiding loss of the "excess" power of 'green' energy plants, and enabling power plants in remote areas and connecting them to new development in other remote areas. A more detailed examination of the economics and policy aspects of the concept must wait until a later paper, where we expect to show how the inclusion of these large-system aspects, typically neglected in engineering concept development, make all the difference here.

CONCLUSIONS

By carefully integrating environmental and energy policy issues, and rethinking the concept of SSP, we show that a viable, realistic, socially and politically acceptable technical path can be laid to realize the dream of Space Solar Power. While a simplistic calculation of end-to-end efficiency shows beamed power transmission to be far inferior to transmission via high voltage lines, a space-based power grid opens up various markets and opportunities that are otherwise closed. The single most important point of the present concept is that it provides the long-sought Evolutionary Path towards Space Solar Power. The inverted thinking of SPG, where we initially beam power into space rather than from it, is the key. Initial system size and scope are kept small to enable deployment and revenue generation, giving time for market forces to identify the opportunities. The production/deployment cost of a 36-satellite system is covered to at least 50% from transmission line costs of the power transacted, with substantial added benefits from carbon cost savings. Advancement to Stage 2 will require improved microwave power handling (waveguide) technology, and in nanoscale fabrication for direct conversion to microwaves.

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