Millimeter Wave Space Power Grid Architecture 2011

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Abstract—The Space Power Grid architecture jump-starts the move towards Space Solar Power (SSP) by setting up a power exchange between terrestrial power plants and customers through Space. A constellation of low-mass, low-risk waveguide satellites starts the first phase. With technical and policy issues settled and the market risk reduced, expansion to full SSP is done using high-altitude ultralight sunlight reflector satellites and 1 GWe converter satellites in mid to low orbits. The baseline architecture published at the 2011 IEEE Aerospace Conference showed the parameter values needed to break even at modest selling price of power and return on investment, inside 50 years from project start, at a total installed level of over 3.4 Terawatts. This architecture is updated with several large improvements and reductions in uncertainty. The waveguide satellites of Phase 1 are now refined using a conceptual design process, and shown to come in under the projected mass. An Intensified Efficient Conversion Architecture (InCA) is used to develop 1 GWe satellites using primary Brayton cycle conversion instead of photovoltaics, delivering very high efficiency and specific power. Several optional paths are explored to reduce power cost and accelerate SSP deployment well beyond 4 Terawatts.

2. INTRODUCTION

The Space Solar Power architecture laid out in this paper makes five departures from the traditional approaches, and shows that these open a clear path to this long-held dream. They are as follows:

1. Use primary Brayton cycle turbomachine conversion of highly concentrated sunlight, rather than photovoltaics to convert solar power in Space to electrical power. This makes an order of magnitude improvement to the specific power (i.e., power generated per unit mass in orbit).

2. Separate out the collection of sunlight, which must be done in high orbits for 24-hour solar illumination, from the conversion which requires large mass. Bring the converters down from Geosynchronous Earth Orbit to 2000 kilometer orbits, thereby decreasing antenna sizes by a factor of over 4, along with a launch cost reduction.

3. Use the atmospheric propagation window at 220 GHz for millimeter wave beaming, rather than 5.8 GHz, thereby achieving a reduction in antenna size by another factor of six. This no doubt incurs technical risk, but the risk appears manageable in view of the rapid progress in millimeter wave technology and its applications.

4. Use tethered and high-altitude, lighter-than-air atmospheric platforms to carry antennae. Millimeter waveguides in the tethers can eliminate the high losses of transit through the wet and dense lower atmosphere, while free-flying stratospheric platforms can act as large relays, enabling beamed power delivery to small antennae on the ground or on tethered aerostats.

5. Use the present imperative to increase terrestrial renewable power generation, with its inherent intermittency, to set up a synergistic Space Power Grid for power exchange as the initial risk-reduction and market establishment mechanism before launching the massive SSP satellites. This opens the way to the global public-private collaboration that is essential to bring about Space Solar Power as a global power solution.

The rationale and basis for each of these is explained in the paper, referring to the progression of the Space Power Grid architecture over the past 6 years. The last four items have been presented before, but the first and most significant
breakthrough is new, and is based on the conceptual design of a 1 GWe converter satellite presented in a companion paper in this conference. The roadmap laid out in the paper shows that full replacement of terrestrial fossil power generation with SSP can be achieved within 31 years from project start, taking into account realistic consideration of the time needed to build the massive infrastructure needed both for the satellites and for the launch facilities and vehicles to deliver and maintain them in orbit.

3. Prior Work

Arthur C. Clarke [1] pointed out in 1945 that the unique properties of the Geostationary Earth Orbit (GEO) suited it to locate a power relay system. The architecture based on a large photovoltaic converter platform located in GEO from where microwaves would be beamed, is credited to Peter Glaser [2], then a Vice President of the Arthur D. Little Company. Construction of such a platform was seen as one of the reasons to develop the Space Shuttle, projecting a launch cost of $220 (in 1960s dollars) per kilogram to LEO in routine, mass production operation. NASA and the Department of Energy studied the concept, with DOE given development responsibility [2], [3]. During the 1980s the first flights of the Space Shuttle, the realization of the immense workload involved in getting each shuttle ready for launch, and the intensified Cold War occupied NASA’s attention. In the 1990s, NASA conducted a Fresh Look study [4] and the evolution of the US Space Station into the International Space Station saw the ISS partners coming together in a program called SPS2000 [5], [6], [7], [8]. Japan appears to be the most serious partner in SPS2000, with scale models and demonstrators being built in Japan [9], [10], and small-scale power beaming studies using microwaves and lasers proceeding steadily [11], [12]. The oil price rise accompanying the Iraq War in 2003 and the Global Warming concerns of the mid-2000s saw another spurt of publishing activity though only JAXA appears to have been focused on hardware advances. The economic collapse of 2008 dimmed interest in Carbon Reduction initiatives even in Europe. However, the Indian imperative towards non-fossil energy resources and the accompanying Nuclear Power initiatives coalesced with the space side of the Strategic Partnership between India and the USA to create a convergence of interests towards Space Solar Power. Recent publications [13], [14], [15], [16] indicate strong interest from both governments and policy think tanks. The dream of limitless electric power beamed down from Space, has remained a dream because of the immense installation cost [17], [18] and lack of an evolutionary architecture. Several initiatives over the decades [19], [20], [21], [22] have sought to show that demonstrator missions were feasible [7], and that they would lead to commercial acceptance [23]. Technology issues have been advanced by several research organizations [24], [25], [26].

The 1979 NASA/DOE studies concluded [3] that SSP was technically feasible but required large investment, and that the US government would eventually fund it by about Year 2050. The technical difficulties and the magnitude of the cost make this prediction look rather optimistic. The traditional approach to SSP started out as an ambitious national effort to lead the world towards a future with unlimited clean electric power. Architecture studies sought to convince national agencies of the imminent practicality of technology demonstrator missions. Thus the primary obstacle cited has been the launch cost, whose reduction is an objective of common agreement. Early support for SSP came from proponents of reusable launch vehicles, leading up to the Space Shuttle transportation system. SSP remained relevant in arguing for the human-carrying STS partly because human construction labor was deemed essential for large Space-based infrastructure. However this also doomed the search for cheap launchers whose unit cost would collapse as demand for mass production rose.

Economic viability in today’s global marketplace means that the return on investment must be adequate to continue to build and operate the system into the regime where SSP becomes a serious contender to replace terrestrial primary fossil power generation, taking into account the finite lifetime of the space and ground infrastructure. This distinction is important in that the problem is not solved when the government, or set of governments agree(s) to fund the first technical demonstration. Since the overall cost per unit power projected for SSP remained one to two orders of magnitude higher than that of competing power generation architectures, no government has shown willingness to make the massive investment needed for SSP demonstrator missions. Dwindling support has accompanied increased stridency in arguing for SSP and against energy alternatives.

Some ball-park numbers serve to illustrate the problem. Terrestrial fossil powered electricity generation is roughly at a level of 4,000 to 10,000 Gigawatts installed capacity. Today the most ambitious claims on specific power, or kilowatts of power per kilogram of mass in orbit, reach only about 0.2 for photovoltaic array satellites, and often lower. This means that 1 GW of power requires at least 5 million kilograms of mass in orbit. Today the best demonstrated cost of launching to Geostationary Earth Orbit (GEO) where most traditional SSP architectures are considered, is between 3,000 and 10,000 US dollars per kilogram. Much lower costs are claimed to be possible with launchers that are just around the corner, but there is no visible proof of such costs being sustainable even if they are achieved in the short term. Let us take the lowest imaginable number of 2,000 US dollars per kilogram. The cost of just launching the needed mass works out to at least 10 billion dollars per GW of electric power, or 10 dollars per watt. This is without adding the cost of manufacturing the satellites or ground infrastructure, the power lines to carry the Gigawatt of power from the ground station, the cost of building stations several square kilometers in extent in orbit, or other major cost items. The total cost is likely to exceed 20 dollars per watt. This compares to the 1 to 3 dollars per watt for installed power generation capacity offered by several terrestrial options. Proponents of SSP point out that a watt of installed SSP capacity is worth up to 4 watts of installed capacity on Earth, so the proper comparison for terrestrial systems would be 4 to 12 dollars per SSP-equivalent watt. Even if the world were ruled by die-hard SSP enthusiasts with infinite powers to command government expenditure and mint dollar bills, 4 Terawatts of SSP will cost around 48 trillion dollars. The point remains that SSP cannot compete on such terms [27].

This does not mean that SSP is hopeless. Bekey [28] proposed a power exchange from North America to a receiver centered on a lake in Japan, through a GEO satellite, citing the high difference in prices of power which permitted an exchange despite the low efficiency of reception. Landis [23] pointed to the opportunities arising from the steep temporal
and geographical variations in price of electric power, such as
the sharp differences in industrial and urban centers. Saiki et
al [12] reported the dramatic advances in efficiency of solar-
pumped lasers, leading to strong consideration of laser-based
modular architectures for SSP. Laser-based architectures of-
fer the strong advantage of small antenna size, limited only
by intensity, so that GEO-based SSP systems can again be
considered, with practical antenna sizes. However, two major
problems keep us from proposing lasers as a near-term SSP
solution. The first is that high-power laser systems, capable
in principle of concentrating hundreds of megawatts of thermal
energy on terrestrial or space locations, fall afoul of inter-
national treaties against the stationing of weapons in Space.
Secondly, there is at present no known proposal for efficient
conversion of laser power in the demonstrated wavebands to
electric power. Photovoltaic efficiencies of conversion for
laser wavelengths still appear to be only around 60 percent at
best. We note that these are not negative predictions against
laser-based SSP. The architecture that we propose is quite
compatible with the use of lasers, and may in fact offer much
more compact systems than what we lay out in this paper.
For these above reasons, we argue that although traditional
SSP architectures have wound up to 3 orders of magnitude away
from practical viability, there are several interesting ways that
do offer improvements by 2 to 3 orders of magnitude.

In Ref. [29] we presented the notion of a viability parameter
k for SSP, and later modified it in Ref. [30] so that it should
approach unity for SSP to become economically viable. The
Viability Parameter k is defined as $k = \frac{25000P}{S/C}$. Here P
is the selling price of space-generated power in $/KWh, \eta
is the efficiency of transmission to the ground, S (kWe/kg) is
the specific power, defined as the power generated in orbit per
unit mass mass needed in orbit to do so and C ($/kg) is the
launch cost to low earth orbit (LEO), with LEO defined here
as the energy level where the chemical propulsion launcher
leaves the payload, to be taken further by a high-specific-
impulse (typically ion) engine. The thumb-rule factor of
25000 is set so that k~1 is where the architecture is rea-
sonably certain to be economically viable at a large scale.
Empirical experience from running various combinations of
architecture variables over the 30 to 50 year period needed to
bring about 4 Terawatts of SSP, led to the finding that with k
approaching 1.0, we could make SSP economically viable.

Table 1 sets out one combination of values that would lead to
a k of 1.0. There may be other, better combinations, but none
that we can see as being practical in the foreseeable future,
without drastic departures from the conventional wisdom on
SSP architecture.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Present</th>
<th>Needed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Price USD/kWe</td>
<td>0.1</td>
<td>0.2</td>
</tr>
<tr>
<td>Beaming efficiency $\eta$</td>
<td>0.5</td>
<td>0.9</td>
</tr>
<tr>
<td>Launch cost c, USD/kg to LEO</td>
<td>3000</td>
<td>1300</td>
</tr>
<tr>
<td>Specific Power S, kWe/kg</td>
<td>0.2</td>
<td>1</td>
</tr>
<tr>
<td>Ground receiver diameter</td>
<td>100km</td>
<td>0.5km</td>
</tr>
</tbody>
</table>

Thus when the massive investment for Gigawatt-level SSP
is needed, it is sought as a predictable addition of capacity
into a well-demonstrated and revenue-generating system with
far lower technical and market risk. This is called the Space
Power Grid (SPG) architecture.

4. Space as a Dynamic Power Grid
The Space Power Grid (SPG) concept uses synergy with the
nascent terrestrial renewable power industry to provide the
boost necessary to make Space Solar Power (SSP) techni-
cally, economically and socially viable on the global scale
needed to make its promised impact on worldwide energy
supply. This concept has evolved since its initial presentation
in 2004, as various means have been found to improve end-
to-end efficiency and reduce the uncertainties in projecting
 technological capabilities, costs and the business case. Re-
 sults from the SPG conceptual design code were presented at
the 2011 IEEE Aerospace conference to explore the prospects
for space to space beaming. That paper was recognized as ‘shifting the conversation on SSP to the millimeter wave
regime’ where there is rapid advancement due to applications
in communications, commercial automotive radar and other
areas.

A following paper at the International Space Development
Conference of the NSS in May 2011 explored an international
collaboration at the initial start up of the system. System pre-
dictions from the SPG code were used to develop an empirical
viability parameter for SSP systems, and show the remaining
distance in refinement of key capabilities. Other work by our
group has surveyed the technical prospects for efficiency and
specific mass using the millimeter wave regime, including
the aspects of MMICs, antenna optimization, location of
receivers and transmitters, and atmospheric losses.

The present paper is triggered by the discussions coming from
the ISDC, on the realization that the roadmap to viable SSP
has become much clearer. It refines the choices in the SPG
parameters, identifies some alternative routes towards vari-
rus related objectives, and reduces uncertainty in prediction.
Specific results and conclusions deal with the following:

1. Refined parameter table with detailed references, to focus
discussion on the input to SSP architecture. Emphasis is
on the specific power, launch cost to LEO and end-to-end
efficiency.
2. Refined overall efficiency predictions.
3. Exploration of alternatives for those who would like to
emphasize or accelerate different steps and paths.
4. Refined identification of research and development needs
to achieve certain key parameters.
5. Results on the need, schedule and hence market for
launchers to deliver the huge mass requirement of worldwide
Some issues raised by SSP enthusiasts and system developers are considered in the paper.

1. Is synergy with terrestrial energy industry really necessary to develop SSP? Is this apparent detour justified? What is the long-term cost and benefit?
2. Is photovoltaic power conversion really the only or even the best alternative at the massive power levels of full-scale SSP?
3. What is the quickest way that we can replace terrestrial fossil power generation with SSP?

Synergy with terrestrial renewable power generation

Clearly, no government will invest the trillions of dollars needed to develop and set up the first large SSP facility, when money is needed to install other forms of terrestrial non-fossil power generation. It is hard to get anyone outside the Space community interested in such an expenditure. However, terrestrial renewables have their own difficulties in competing with established utilities, because solar and wind plants are fundamentally intermittent in generation. Using Space as a power grid, we propose to connect generation plants all over the world in essentially real time. The revenue comes from the ability of participating power plants to win higher prices for their output, to use their peak generation without large on-site storage, to avoid the need for 100 percent redundant auxiliary generation capacity (usually fossil-fuelled), and to avoid having to set up local grid capacity to handle their peak output. The Space Power Grid would also enable participants to sell their power to island and remote communities on a retail basis, so that they can command higher prices than what they can obtain in local markets served by the terrestrial grid.

Thus in Phase 1, the SPG consists of pure relay spacecraft, conceptually equivalent to waveguides, but with dynamic receiving and transmitting antennae, active cooling systems and orbit-correcting propulsion. Phase 1 parameters are detailed in Ref.[29]. The Phase 1 system was shown to be quite effective and viable, expanding to 100 satellites serving 250 ground stations by Year 17. Figure 2 from [31] shows the concept. Table 2 from the same reference, shows conceptual design parameters. These are 4000 kg class satellites placed into 2000 km sun-synchronous or near-equatorial orbits. The antennae are small enough to enable each craft to be packed into the payload bay of a single launcher.

This is just one embodiment of the system. Numerous permutations of launch rate, orbits and satellite/ power transaction size are possible, and rigorous optimization of the system is left to future work. Figure 1 shows the general schematic of the Space Power Grid approach.

5. GIRASOLS AND MIRASOLS

As the first generation craft of the SPG reach retirement in 17 years, much larger Phase 2 craft are launched to replace them. We call these Girasols because they constantly turn to receive sunlight. These are solar power converter craft, conceptually designed to a 1GWe power level. They also perform the relay function of the Phase 1 craft, though the need for any such power relay gradually disappears once the Girasols become prevalent. In the SPG architecture, the Girasols are by far the most costly and massive items. Their collectors are sized to receive highly intensified sunlight, from ultra-light reflectors.

The SPG architecture separates the large area needed to collect enough sunlight to generate a Gigawatt of electric power, from the conversion and power beaming functions. We conceptualize the solar farms as ultralight reflectors in orbits that are high enough to be in perpetual sunlight, rather than be hard linked to the Girasols. We call these high-orbit reflectors Mirasols because they perpetually view the Sun. To reach 4TWe of Space Solar Power, over 4000 Girasols and 4000 Mirasols would be needed. Future developers may standardize a design converting much more than 1GWe, but at present we see no advantage to that. Figure 1 schematically illustrates the Mirasols (high-altitude reflectors), the Girasols (converter-relays in the grid orbits) and the small Phase 1 relays.
6. DEVELOPMENTS IN ASSUMPTIONS

Waveguide Satellite for Phase 1

The major technical risk in the SPG architecture is the argument to adopt millimeter wave conversion and beaming. The state of the art in this technology and applications was summarized in [32]. The new satellite design proposed for the Space Power Grid was the Phase 1 power exchange satellite, which was imagined as antennae connected through low-loss waveguides, to redirect beamed power with minimal on-board loss. The conceptual design of the Phase 1 waveguide satellite was undertaken by Dessanti et al [31]. Suitable waveguide components were found, the antennae were properly sized for well over 96 percent capture at 220 GHz, and a more refined estimate was made of the active thermal control (ATCS) system and orbit-correction propulsion requirements of the satellite. With these, the new mass estimate of the satellite at launch was 3625 kg, comfortably below the 4000 kg estimate used in [29]. This mass is used in the new calculations done for the present paper.

Specific Power

The Intensified Efficient Conversion Architecture (InCA) concept for the Girasol satellite is presented in another companion paper at this conference [33]. This argues that PV architectures achieve no better than linear scaling of power with mass, regardless of the total power generated. In contrast, gas turbine heat engines achieve a large nonlinear advantage in specific power as the power level rises. Thus, for a 1 GW craft, the InCA uses primary Brayton cycle conversion from highly intensified solar heating, to mechanical and thence to electrical and beamed millimeter power. Figure 4 shows the general arrangement, including an option that we considered, for spectral separation and efficient narrow-band photovoltaic conversion of some spectral lines ahead of the primary Brayton cycle converter. The extreme temperatures that can be reached in Space allow a cycle efficiency of 80 percent for conversion, rendering even narrowband photovoltaic conversion uncompetitive in comparison. At high power levels, Brayton cycle gas turbines achieve several times the specific power that photovoltaic conversion can achieve. The net result is that the specific power of the entire space portion of SPG in the full SSP phase, goes up to 1.61 kW per kg in orbit. With spacecraft costs estimated based on mass as done traditionally in NASA and US Air Force public-domain cost estimation processes, the total investment needed in the system plunges, and the viability improves immensely. A conceptual sketch of the Girasol is shown in Figure 5.

Launch and Orbit Transfer Costs

In our architecture, the Phase 1 waveguide satellites are assumed to be launched by present-day launchers of the Boeing Delta-2 class, so that launch costs are also assumed to be at present-day levels of 2,500 dollars to LEO, with spiral-trajectory low-thrust electric propulsion of 5300 seconds specific impulse used to move the satellites to their final sun-synchronous or near-elliptical orbits. The Phase 2 and 3 average launch costs are assumed to come down to 1,300 dollars per kilogram. All SSP architectures assume very low launch costs of either 220 or 880 dollars per kilogram to LEO. The basis for this assumption is that Reusable Launch Vehicles (RLVs) capable of routine operations with several launches every hour, will be developed in time. The precise type of RLVs is open to debate.

Selling Price of Power

There are wildly varying opinions about the projected price that can be obtained for space-generated electric power. Some experts claim that the price can be brought down as low as 0.04 dollars per kWh. Others claim that it will have to be 0.4 dollars. In our initial architecture, the system broke even...
by Year 50 with a price of 0.20 dollars per kWh. One issue is whether a substantial reduction can be achieved, and at what cost in system deployment speed. Given that interest rates today are at all-time lows, a modest ROI for this enterprise may be a defensible assumption despite the obvious risks.

**Beaming Efficiency**

Our previous work projected that 90 percent transmission through the atmosphere could be achieved with 220 GHz millimeter waves. This requires that the air be cool and dry, and the ground station located in a high desert or mountain ridge. In wet weather, some form of burn-through would be needed; however, given the lock-in time of many minutes per ground station per satellite, it appeared to be reasonable that the first few seconds of beaming at a high power level would be used to burn a conducting or non-dissipative path through the lower atmosphere. Recently we have identified another option for such beaming through wet weather. This is to use antennae mounted on hydrogen-filled aerostats tethered at 4000 to 5000 m above sea level. Such an approach is described in [34] from where Figure 6 is taken.

**Millimeter wave generation and beaming**

Millimeter wave generation from high-frequency alternating currents has uncertainties; however, present predictions are that this generation can be done with an efficiency of over 90 percent using millimeter wave amplifier systems. The mass penalty of this conversion was conservatively estimated using specific power values obtained in the 1980s. The issues in millimeter wave generation and beaming are summarized in [32].

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**System Startup**

An opportunity to start up the global constellation of waveguide satellites and explore the opportunities in international collaboration, opened with the interest in a US-India partnership towards SSP. Scenarios using 2 satellites and 4 countries, or 6 satellites and two countries, were explored, with the latter providing near-24-hour coverage. These satellites would be located in 5500 kilometer orbits. As the number of satellites increases, these would also be brought down to the 2000 km level of the standardized waveguide satellites. Some authors have considered the use of Molniya orbits where the satellite stays generally above a given point on Earth for a long time in each orbit. We do not favor use of these, because of the large variation in the size of ground antennae needed as the beaming distance changes substantially.

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**7. Assumptions and Parameter Choices**

In Table 2 the present assumptions and parameter choices of the Space Power Grid architecture calculation are listed, going from choice of frequency and altitude, to the Net Present Value calculation to ensure breakeven by Year 17 for Phase 1 and Year 50 for 4 Terawatts of installed SSP. Some parameters change between Phase 1 and Phase 2-3. These data are reproduced from [29]. Most important of these assumptions is the launch cost to LEO. In Phase 1 it is around $2500 per kg, but in Phase 2 and 3 we assume that it comes down to $1300 per kg or lower because of the seriousness factor. In other words, with Phase 1 working and seen to be making money, we can believe that investors in Reusable Launch Vehicles and other such technologies will start bidding on mass launch operations over several decades.
and accordingly, projecting low unit costs.

8. BASES OF PARAMETER VALUES

1. B1: The 220GHz window offers up to 90% transmission through a dry atmosphere, compared to 95% below 10GHz, and 92% at 140GHz. Above 10GHz, wet weather operation is poor at low power levels. Continuous megawatt-level beaming through a raincloud remains to be explored. With the tethered aerostat option presented later in this paper, low-loss transmission through the lower atmosphere is enabled using waveguides built into the tethers.

2. B2: Solar power can be converted to DC using high-intensity PV arrays at over 42% efficiency [39], and from DC to microwave beamed power with roughly 80% efficiency [40]. We assume 40% efficiency with 220GHz conversion. Direct conversion using optical antennae, perhaps made of nanofibers [41] may offer efficiencies well above 40%. Theoretically, 80% conversion is possible. The Intensified Conversion Architecture (InCA) design for the Girasol argues that over 80 percent conversion efficiency can be achieved using primary Brayton cycle conversion.

3. B3: 80% conversion from line frequency to beam microwaves has been demonstrated. We projected initially that conversion to 220GHz can reach at least this efficiency. However, for single-frequency conversion to 220 GHz, modern solid state amplifiers achieve over 90 percent conversion.

4. B4: A reciprocal conversion efficiency of 90% is deemed possible for the same reason.

5. B5: Atmospheric propagation data at 220GHz [42].


7. B8: Areal density of 3 to 7 grams per square meter are cited for solar sail craft. Naval Research Laboratory estimate, 2008, of the areal mass of large solar sails [43] including their support structures is much smaller than the value that we have assumed.

8. B9: A 5% allowance for other systems is conservative compared to [16], but we have not detailed the subsystems.

9. B10: Reflector may be similar to B8, but some thermal control is needed in view of the intensified sunlight, and lower Phase 2 orbits demand stronger structures.

10. B11: Converter mass per unit power is a critical limiting technology. We assume this value of 0.5 Kg/MWe at large power levels with 300-sun intensified sunlight. It is feasible with direct conversion or mechanical-electric conversion.

11. B12: The Phase 1 SPG satellite is conceptualized with direct conversion using optical antennae, perhaps made of nanofibers [41]. We assume 40% efficiency with 220GHz conversion to 220GHz can reach at least this efficiency. How-ever, for single-frequency conversion to 220 GHz, modern solid state amplifiers achieve over 90 percent conversion.

12. B13: With 220GHz, the antennae is sized for 96.1% capture with an Airy constant of 10.49 in the equation for diffraction-limited antenna size, rather than the 84 percent achieved with a constant of 2.44. .

13. B14: Ground antenna efficiency is taken as 0.9 based on claims of people in the microwave beaming community.

14. B15: The effective diameter of the receiving antenna on the Phase 1 spacecraft is taken to be 50m.

15. B16: Orbit height of 1900+ miles enables a sun-synchronous orbit where each satellite stays in view for a few minutes each time.

16. B17: Each ground station is assumed to have a clear view of the sky down to 45 degrees from the zenith. This is conservative, but atmospheric propagation loss data are available for 45-degree transmission [42].

17. B18: A design distance of 2400km is chosen for intersatellite beaming, to size the space antennae. When used for longer distance beaming, this implies either a loss at the

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**Figure 6.** Millimeter wave power beaming using antennae mounted inside aerostats.

**Table 2.** Space Power Grid Baseline Parameter Choices.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Basis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Frequency (GHz)</td>
<td>220</td>
<td>B1</td>
</tr>
<tr>
<td>Conversion efficiency solar to beam</td>
<td>0.72</td>
<td>B2</td>
</tr>
<tr>
<td>Conversion AC to mmwave</td>
<td>0.9</td>
<td>B3</td>
</tr>
<tr>
<td>Conversion 220GHz to ground AC</td>
<td>0.9</td>
<td>B4</td>
</tr>
<tr>
<td>Efficiency of atmos. pass</td>
<td>0.9</td>
<td>B5</td>
</tr>
<tr>
<td>Transmitting Space Antenna kg/m²</td>
<td>0.05</td>
<td>B6</td>
</tr>
<tr>
<td>Receiving Space Antenna kg/m²</td>
<td>0.05</td>
<td>B7</td>
</tr>
<tr>
<td>Ultralight Reflector Satellite kg/m²</td>
<td>0.01</td>
<td>B8</td>
</tr>
<tr>
<td>Miscellaneous mass added</td>
<td>5%</td>
<td>B9</td>
</tr>
<tr>
<td>Collector kg/m² of converter sat</td>
<td>0.05</td>
<td>B10</td>
</tr>
<tr>
<td>Converter kg/MWe at 300 Suns</td>
<td>500</td>
<td>B11</td>
</tr>
<tr>
<td>Efficiency of reception at Satellite</td>
<td>0.961</td>
<td>B12</td>
</tr>
<tr>
<td>Efficiency of capture at ground</td>
<td>0.961</td>
<td>B13</td>
</tr>
<tr>
<td>Efficiency of ground antenna</td>
<td>0.9</td>
<td>B14</td>
</tr>
<tr>
<td>Diameter of Phase 1 sat receiver, m</td>
<td>50</td>
<td>B15</td>
</tr>
<tr>
<td>Orbit height of Phase 1 sat, km</td>
<td>2000</td>
<td>B16</td>
</tr>
<tr>
<td>Half-angle of azimuth visibility, deg.</td>
<td>45</td>
<td>B17</td>
</tr>
<tr>
<td>Distance between satellites (km)</td>
<td>2400</td>
<td>B18</td>
</tr>
<tr>
<td>Power transmitted (design, MW)</td>
<td>60</td>
<td>B19</td>
</tr>
<tr>
<td>Phase 2 collector diameter, m</td>
<td>300</td>
<td>B20</td>
</tr>
<tr>
<td>Cooling system kW/MW of heat</td>
<td>400</td>
<td>B21</td>
</tr>
<tr>
<td>Launch cost to LEO, Phase 1 $ per kg</td>
<td>2500</td>
<td>B22</td>
</tr>
<tr>
<td>Launch cost to LEO, Phase 2-3$ per kg</td>
<td>1300</td>
<td>B22</td>
</tr>
<tr>
<td>Isp for orbit transfer, sec.</td>
<td>5300</td>
<td>B23</td>
</tr>
<tr>
<td>Operations cost per sat $M</td>
<td>5</td>
<td>B24</td>
</tr>
<tr>
<td>Satellite other systems mass:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ground facilities development $M</td>
<td>1000</td>
<td>B25</td>
</tr>
<tr>
<td>$M cost per ground facility cost</td>
<td>25</td>
<td>B26</td>
</tr>
<tr>
<td>$ per kw to produce power, ground</td>
<td>0.04</td>
<td>B27</td>
</tr>
<tr>
<td>Sales price, $ per KWh, Phase 1</td>
<td>0.17</td>
<td>B28</td>
</tr>
<tr>
<td>Number of stations participating</td>
<td>250</td>
<td>B29</td>
</tr>
<tr>
<td>MW average per plant</td>
<td>60</td>
<td>B30</td>
</tr>
<tr>
<td>Assumed Discount Rate, percent</td>
<td>6%</td>
<td>B31</td>
</tr>
<tr>
<td>Desired Return on Investment, Ph1 %</td>
<td>6%</td>
<td>B32</td>
</tr>
<tr>
<td>Desired Return on Investment, Ph2 %</td>
<td>6%</td>
<td>B33</td>
</tr>
<tr>
<td>Loan percentage, Phase 1</td>
<td>30%</td>
<td>B34</td>
</tr>
<tr>
<td>Loan percentage, Phases 2 and 3</td>
<td>30%</td>
<td>B35</td>
</tr>
<tr>
<td>Sales price, $ per KWh, Phase 3 SSP</td>
<td>0.11-0.15</td>
<td>B36</td>
</tr>
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</table>

...
The rate was ramped up at a pace consistent with risk management. Beyond the first launch, the launch ramping up the SSP rapidly.

In Phase 1, a 5-year development period was assumed, before the first satellite launch. Beyond the first launch, the launch rate was ramped up at a pace consistent with risk management and the practical speed with which ground facilities would come on-line to participate in the SPG power exchange. A high initial launch failure/de-orbit rate was also taken into account. With these constraints, breakeven was sought within the 17-year design life of the first satellite launched, at a level of approximately 100 satellites and 200 to 250 ground stations. During this phase, the revenue to the SPG system was set at approximately 0.04 US dollars per kWh delivered, and this was used to arrive at the selling price required. This system exhibits several features:

1. There is a minimum level of power that must be transacted per satellite for viable operations, since there are fixed costs of operation. This level was studied in [35] and found to be 10 MW; however, we optimized on 60 MW. This level is high enough to attract the participation of ground stations with only moderate risk and substantial reward, since it is high enough to enable the ground station to compensate sharp fluctuations and provide a minimal level of supply even if other alternatives are down. It also allows these stations to sell off their power spikes at lucrative rates, minimizing their need for local storage and impedance matching to deal with such surges. Note that in a worst case scenario, even if there is no satellite overhead, a station can simply use its transmitter to dump excess load into Space, though we do not expect that this will be needed.

2. The 60 MW level is adequate for many smaller communities, and hence is suitable for retail delivery to community receivers, in lieu of running their own generating stations.

3. This level provides a reasonable utilization of the antenna areas that are dictated by orbit height and frequency.

The constellation number of 100, and the 250 ground stations, were chosen simply to study the progression to a stable steady state, and see the parameters needed for breakeven. Note that with 100 satellites continuously transacting 60 MW, the total power level being transacted is a measly 6 GW, about the output of one modern nuclear power plant. Once the point is proven with relatively low risk, the SPG thus has room for expansion by orders of magnitude. Thus, concerns from proponents of GEO-based SSP, about enough satellites being available for continuous beaming (which can be done with a constellation of around 36 satellites) are quite misplaced to the point of being specious.

The other aspect that has generated concern from SSP enthusiasts is our delaying the start of Phase 2 until 17 years after the first Phase 1 launch, which is Year 23 of the program. There were two reasons behind this.

1. This would buy enough time to pursue the best conversion options for Phase 2, with the seriousness imparted by an ongoing Phase 1 project. It should be evident that the SSP community is nowhere near a point where the technology for the Gigawatt-scale SSP satellite has reached satisfactory levels of specific power to enable freezing the design with any hope of economic viability.

2. We wanted the Phase 1 progression to breakeven to be clearly visible, before incurring the massive investment and negative NPV that are inevitable with development of the full-scale SSP satellite.

With the demonstration in [33] that Phase 1 would break even with zero space-based power generation, and the demonstration in [33] that the specific power needed for full-scale SSP can be achieved using the Intensified Conversion Architecture using primary Brayton cycle conversion, both of the above constraints can now be relaxed.

Baseline SPG system from March 2011

The baseline SPG system described in [29] set a target of reaching zero NPV at a specified ROI (as the definition of break-even) in a set number of years from project Phase 1 startup, while reaching as close as possible to the desired goal of installed capacity. The input parameters were iterated within the range of defensible reason, to achieve the highest installed capacity within the above constraints.
For the Phase 2 buildup of SSP, Reference [29] set the constraint that breakeven had to be achieved by Year 50 of the overall project, with development expenditure starting only in Year 17 as the first Phase was breaking even. The ramp-up rate becomes crucial here, as the investment is massive. The constraint is the sheer amount of debt that must be incurred. Even at costs of financing that can be negotiated by multinational government-industry consortia, the ramp rate must be limited. The other obvious constraint on ramp rate is the availability of launcher capacity. A specific power of 1 kWe per kg implies launching a bare minimum of 1 million kilograms, equivalent to 10 launches of the largest heavy-lift systems on the drawing board for each 1 GWe SSP satellite. Several more launches will be needed to convey the assembly robots and other infrastructure. Thus deploying even one 1 GWe satellite per year, appears to be a stretch of the imagination. At least 4000 such satellites, plus a few to replace failed deployments, must be launched to reach the target of 4 TWe SSP. Each satellite will then require periodic maintenance and repair. This doubtless requires a revolution in Space launch technology and infrastructure.

The above is not at all unique to the SPG architecture for SSP. If the specific power is only 0.2 kWe per kg as cited for the most advanced of GEO/5.8 GHz-based SSP systems, then the launch requirement is at least five times that described above. If all the mass has to reach GEO (versus 10 percent in GEO and 90 percent in 2000 km orbits as in SPG) that adds to the size or decreases the payload of each launcher. SSP enthusiasts argue that this demand will set off a Space Launch Race that will justify the development of runway-operated large launchers, and collapse the launch cost by one to two orders of magnitude. They also imagine the advent of runway operations at the rate of several launchers an hour, versus the presently-demonstrated reality of several per year. It must be noted in passing that during the Cold War, the US, USSR and PRC planned to launch some 50,000 space-capable ballistic rockets within a few hours and wipe out humanity, so a determined multinational effort can no doubt achieve far better than today’s low rate of launches. Proposals for Equatorial runway launch facilities include one to place such facilities at the old WW2 airfields in Papua-New Guinea [36].

In our baseline architecture, we assumed no such miracle. The launch cost per unit mass was assumed to drop from $2500 per kg in Phase 1, to $1300 per kg in Phase 2 due to the clear and stable prospect of large demand.

9. RESULTS

Phase 1 baseline

The new baseline calculation uses the refined mass and size of the Phase 1 waveguide satellites, but leaves intact the Phase 2 and Phase 3 satellite projections from Reference [29], where we assumed a direct conversion system that could achieve 40 percent conversion from sunlight to electric power. The major change made is that the Phase 2 and Phase 3 development starts immediately at the start of the project, and the first Phase 2 launch comes in Year 12, which is 6 years after the first Phase 1 launch. Launching the massive Phase 2 satellite sooner does not appear to be practical even if it were wise from the technical risk point of view. Figure 7 summarizes the results. The first Phase 2 satellites generate power just as Phase 1 launch expenditures are ending, resulting in a major spike in NPV in years 13 through 15. The massive expenditures of Phase 2 and Phase 3 ramp-up then starts a deep dip beyond that. The drop in launch cost from $2500 per kg in Phase 1 to $1300 per kg for Phase 2 is not assumed to apply to any remaining Phase 1 launches, as those will presumably use the same launchers as they did before as part of a long-term contract. Iterations on the launch cost showed that Phase 1 launch cost is not a major driver of the overall system cost of Phase 1, given the small mass of each satellite. In Phase 1, the selling price of power could be taken down as low as $0.17 per kWh. The differences between the three curves in the figure that diverge showing different prices for Phase 2, will be explained later.

Figure 7. Net Present Value evolution in the Phase 1 Space Power Grid using results from refined estimates of satellite mass, and a selling price of 17 cents per kWh for ground-generated power exchanged through Space. Phase 2 satellite launches start in Year 12. Breakeven occurs in Year 13, followed by a sharp upward spike as Phase 1 matures and the first Phase 2 satellites add revenue, then plunges sharply as Phase 2 expenditure ramps up.

Figure 8 shows the assumed ramp-up rate in deployment of Phase 2 and Phase 3 SSP generation. This explains the sharp dip in NPV by Year 17 shown in Figure 7. The ramp is set to expand SSP capacity beyond 4 Terawatts around Year 40, and reaches 5.61 Terawatts by Year 50. Presumably there will be expansion to over 8 Terawatts, but the limiting values and the ramp-down phase towards steady-state operations is not considered here. The investment implications of the ramp rate are shown in Figure 9. For now, let us focus on the curve marked with triangles, denoting the new accelerated Phase 2 deployment baseline with 40 percent conversion technology, at a selling price of 11 cents per kWh for SSP. The good news is that breakeven comes by Year 47 even at such a selling price. The bad news is that the negative spike in NPV, which basically implies the level of investment needed, reaches an immense 10 Trillion dollars around Year 20. The implications for the global economy of this level of expenditure, gives pause, but this is the best reality that can be imagined with a specific power of around 1 kW / kg.
Effect of InCA design for the Girasol SPS

We next present the effect of including the Intensified Conversion Architecture [33] on the deployment replacing terrestrial primary power with SSP. The change in Phase 1 is small but noticeable, since the first 1 GWe satellite launched now has a significantly lower mass. The Girasol 1 GWe converter spacecraft is shown to scale in Figure 10. The specific power for Phases 2 and 3 (Girasol 1 GWe converter in 2000 km orbits, and Mirasol sunlight collector satellites in high orbits to supply each Girasol) reaches 1.675 kWe per kg in orbit. This has a dramatic effect on the viability parameter k. The effect is shown in comparison to the baseline, in Figure 9. The NPV at a selling price of 11 cents per kWh is shown for comparison with the baseline, the effect being breakeven by Year 31 and the negative spike in NPV now limited to a relatively small 3 Trillion dollars, occurring around Year 25. If the selling price for power is slashed to 6 cents per kWh, realizing the dream of low-cost, plentiful, clean power, the NPV dip reaches 9 Trillion dollars and breakeven now occurs only in Year 48, by which time the installed level has reached close to 5 Terawatts as seen from Figure 8.

Breakeven Year vs. Selling Price

There are numerous variables with uncertainty in any move towards SSP. In the above, the selling price, the expected return on investment, the cost of financing, the depth of the NPV trough that can be tolerated, and the years to breakeven, are obvious variables. Figure 11 shows how the year where breakeven occurs, varies with the selling price of power in Phases 2 and 3. In all these, Phase 1 achieves breakeven in Year 13, so the variable is the year when breakeven occurs in the ramp-up to Terawatt-level SSP. The baseline system using conversion efficiency of 40 percent, cannot sustain a selling price below 11 cents per kWh. However, with higher prices, up to 15 cents, breakeven can be achieved as early as Year 31 with a selling price of 11 cents, but the price can be brought down as low as 6 cents and still break even before Year 50. The tradeoff between selling price, NPV trough and breakeven year, involves global financing and political issues that are far beyond the scope of this paper, besides being subject to zeroth order uncertainty.

Viability Parameter vs. Selling Price

One way to compare SSP architectures as stated in the Introduction, is to use the Viability Parameter k, incorporating specific power, launch cost to LEO, beaming efficiency and price of power. The variation of k with selling price of power is shown in Figure 12.

Why have the Phase 1 power exchange?

Most SSP enthusiasts still do not accept that deployment of a large SSP satellite will not occur without strong support from the terrestrial renewable energy community and the notion of Space as a power grid. Also, the space launch industry will not ramp up to the level needed to launch several GW-level SSP satellites per year, until that market has been clearly proven. These arguments imply that the first Phase power transfer satellites, with their relatively miniscule cost and
risk, are absolutely essential to make Phase 2 deployment feasible. It is interesting to note from the NPV calculations, that launch cost is no longer a major driver of cost in Phase 1 compared to other system development costs, since the waveguide satellites have so little mass. Hence one of the primary bottlenecks to SSP has been broken, giving a low-risk, short-term demonstration path to the most risky technologies proposed in the SPG architecture.

Thus we keep the 100-satellite, 250-station Phase 1 intact, but simply shift development of the Girasols and Mirasols forward to proceed in parallel. Thus first launch of a Girasol is projected to occur by Year 12 of the project (takes longer than the Phase 1 satellites, for both the Phase 2 and 3 satellites, as well as for ground stations to receive the much larger amount of power, besides providing a small cushion to deal with surprises in the millimeter wave power exchange technology of Phase 1). The above calculations, optimistically assuming that space launch capability will ramp up at amazing speed (to synchronize assumptions with the GEO-based SSP enthusiast community) imply then that the Phase 2 system can break even by Year 31 at around 2.5 Terawatts, and proceed to exceed 4 TWe before Year 40. Thus we can have full-scale SSP within 30 years. In other words, if governments were to miraculously give a “go-ahead” by late 2012, fossil-based electric power generation and smoke stacks would be quaint history to children in 2042.

It is useful to ponder what this does to the terrestrial renewable power community that supported Phase 1. In fact, the only change is that after about 10 years of participation in the Phase 1 power exchange, they will stop being asked to beam power out to sell with 50 percent loss in some other part of the world. They will simply use their receivers to collect space-based power, at costs that will be comparable, even slightly higher, than what they can generate themselves when the sun shines or the wind blows over their plants, and be assured of a round-the-clock power supply to their customers. On the other hand, an effort to arm-twist the governments to fund pure SSP without the participation of these suppliers, will not be nearly as attractive to them.

10. CONCLUSIONS

This paper refines the architecture of the Space Power Grid approach to Space Solar Power. It incorporates an improved conceptual design of the Phase 1 waveguide satellite, and an initial conceptual design of the Phase 2 Girasol 1 GWe SSP satellite. Specific conclusions are:

1. The Girasol Brayton cycle Intensified Conversion Architecture offers far better efficiency, much higher specific power, and a shorter technology path than the direct conversion options previously considered for full-scale Space Solar Power.

2. The technical risk and uncertainties in mass and efficiency in developing millimeter wave conversion and beaming, remain as the major risks in SSP development. The Phase 1 Space Power Grid offers the opportunity to completely address these before the first 1 GWe satellite has to be launched.

3. The optical linking between the Mirasol high-orbit collectors and the Girasol converter satellite, remains to be verified, along with refining the mass estimate for the Mirasol.

4. Both satellite conceptual designs, for the Phase 1 waveguide satellite and the Phase 2 Girasol satellite, come in well under the mass estimates laid out in the prior iteration of the SPG architecture, thereby reducing the uncertainty in the technological and economic projections. Clear technological paths if not existing material and component choices have been identified for several of the components considered to be the most technically risky in the previous iteration.

5. Since the viability of both Phase 1 and Phase 2 are independently demonstrated, overlapping development is considered, to reduce the time to deployment of Space solar power generation on a large scale.

6. With the first 1 GWe satellite launched 6 years after the first Phase 1 waveguide satellite, the baseline 40-percent efficient system is shown to reach 4 Terawatts by Year 40, breaking even by Year 43 at a power selling price of 11 cents, but with an NPV trough of nearly 10 Trillion dollars.

7. The Intensified Conversion Architecture achieves breakeven by Year 31 with a much smaller NPV trough less than 3
Trillion dollars, at a selling price of 11 cents per kWh, or can break even by Year 48 with an NPV trough of 9 Trillion dollars, at a selling price of 6 cents per kWh.

8. At the ramp rate used in these calculations, SSP installed capacity can exceed 5.6 Terawatts by Year 50 from project start.

9. Values of viability parameter k in the region of unity, result in viable SSP architectures.

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BIOGRAPHY

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Brendan Dessanti received his B.S. degree in Aerospace Engineering from the Georgia Institute of Technology in 2011 and is currently pursuing an M.S. Degree in Aerospace Engineering from Georgia Tech. Brendan is a graduate research assistant for the Experimental Aerodynamics and Concepts Group at Georgia Tech and leader of the Space Power Grid student team. His research focuses on space systems design as it applies to space-based solar power. Brendan has obtained invaluable experience from internships at Sikorsky Aircraft, HEICO aerospace, and various aircraft parts. At Sikorsky, he analyzed flight loads for the Black Hawk Helicopter as a member of the Loads and Survivability group; at MIT Lincoln Laboratory, analyzed gravitational harmonics for the purpose of missile flight simulations in the Missile Defense Systems Integration group; and at SpaceWorks Enterprises performed various analysis and presentation preparation tasks in support of NASA Lunar Surface Systems cost estimating and system integration.

Shaon Shah is a senior in the school of aerospace engineering at G.I.T. He has been participating in research with the Experimental Aerodynamics and Concepts group. Early in the development of the InCA scheme for Space Solar Power generation, he researched and identified materials to push the temperature limit for solar heating beyond 4000K. He has been working on identifying materials and options for high temperature solar concentrators, as well as thermoelectric, thermophotovoltaic and narrow-band photovoltaics.

Richard Zappulla received his B.S. degree in Aerospace Engineering from the Georgia Institute of Technology in 2011 and is currently pursuing an M.S. degree in Aerospace Engineering from Georgia Tech. Richard is a Graduate Researcher with the Space System Design Laboratory and the Experimental Aerodynamics and Concepts Group. His research focuses on the development of novel launch systems for CubeSats as well as Spacecraft Systems Development, in particular, the Command & Data Handling and Flight Software systems. Additionally, Richard is the Project Manager for Georgia Tech's NASA University Student Launch Initiative (USLI) team. Richard has gained invaluable experience from internships and CO-OPS at the Jet Propulsion Laboratory (JPL) and HEICO Aerospace. While at JPL, he was responsible for the development and testing of the Wind Guard System for the Mars Science Laboratory (MSL) sample drop-off system; at HEICO aerospace, he gained experience from internships and CO-OPS at the Jet Propulsion Laboratory (JPL) and HEICO Aerospace. While at JPL, he was responsible for the development and testing of the Wind Guard System for the Mars Science Laboratory (MSL) sample drop-off system; at HEICO aerospace, he gained experience from internships and CO-OPS at the Jet Propulsion Laboratory (JPL) and HEICO Aerospace.

Nicholas Picon is in his second year at Georgia Tech pursuing his B.S. degree in Aerospace Engineering. He is also working on his minor in Computer Science with a concentration on Artificial Intelligence. Nicholas has spent three semesters working in the Experimental Aerodynamics and Concepts Group at Georgia Tech, where his main role was designing constellations to optimize coverage time for various orbital networks. Nicholas has co-authored several papers on the subject of wireless power transfer through space and advised Boeing on trade studies requiring optimization of orbital networks. He plans to intern with Rolls-Royce in the Summer.

REFERENCES


