Millimeter Wave Space Power Grid Architecture Development 2012

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Abstract—This is an update of the Space Power Grid architecture for space-based solar power with an improved design of the collector/converter link, the primary heater and the radiator of the active thermal control system. The Space Power Grid offers an evolutionary approach towards TeraWatt-level Space-based solar power. The use of millimeter wave frequencies (around 220GHz) and Low-Mid Earth Orbits shrinks the size of the space and ground infrastructure to manageable levels. In prior work we showed that using Brayton cycle conversion of solar power allows large economies of scale compared to the linear mass-power relationship of photovoltaic conversion. With high-temperature materials permitting 3600 K temperature in the primary heater, over 80 percent cycle efficiency was shown with a closed helium cycle for the 1GW converter satellite which formed the core element of the architecture. Work done since the last IEEE conference has shown that the use of waveguides incorporated into lighter-than-air antenna platforms, can overcome the difficulties in transmitting millimeter wave power through the moist, dense lower atmosphere. A graphene-based radiator design conservatively meets the mass budget for the waste heat rejection system needed for the compressor inlet temperature. Placing the ultralight Mirasol collectors in lower orbits overcomes the solar beam spot size problem of high-orbit collection. The architecture begins by establishing a power exchange satellite is proposed to gather required data through the moist, dense lower atmosphere. A graphene-based radiator design conservatively meets the mass budget for the waste heat rejection system needed for the compressor inlet temperature. Placing the ultralight Mirasol collectors in lower orbits overcomes the solar beam spot size problem of high-orbit collection. The architecture begins by establishing a power exchange satellite with a launch cost reduction. Runway-based launch and landing are required to achieve the launch productivity as well as the cost reductions to enable such a large deployment on schedule. Advancements in the certainty of millimeter wave conversion technology and runway-based space access, are seen to be the outstanding issues in proceeding to full-scale Space Solar Power.

10 IMPLICATIONS FOR RUNWAY-BASED LAUNCHERS ............................................. 8
11 SUMMARY OF NEEDED RESEARCH AND DEVELOPMENT .................................. 9
12 CONCLUSIONS ................................................................. 9
ACKNOWLEDGMENTS ......................................................... 9
REFERENCES ................................................................. 9
BIOGRAPHY ................................................................. 10

1. NOMENCLATURE

GEO Geo-Stationary Earth Orbit
Girasol SSP converter satellite
GW $c$ Launch cost to LEO, in US dollars per kg of payload in LEO
$k$ Viability Parameter for SSP architectures
$kW$ kiloWatts. One thousand Watts
$kWh$ kiloWatt-hours.
LEO Low Earth Orbit
Mirasol Ultralight solar collector satellite
MW MegaWatts. One million Watts
NPV Net Present Value
$P$ Price of electric power, US dollars per kWh
PV Photovoltaic
ROI Return on Investment
SSP Specific Power, kW to Earth per kg in orbit
SPG Space Solar Power
TW TeraWatts. One thousand GigaWatts
$\eta$ Efficiency of transmission to Earth

2. INTRODUCTION

This is an update on the development of an economically and technically viable architecture for Space Solar Power (SSP). As presented in Reference [1], the Space Power Grid (SPG) 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.
2. Separate out the collection of sunlight 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 eliminate the high losses of transit through the wet and dense lower atmosphere, while free-flying stratospheric platforms can act as relays 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 various elements of this architecture are illustrated in Figures 1 and 2. The rationale and basis for each of these is explained in the paper, referring to the progress 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.

The conclusions from [1] were:

1. The Girasol Brayton cycle Intensified Efficient Conversion Architecture (InCA) 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 I 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 selling price of 11 cents per kWh, 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 then 3 Trillion dollars, at a selling price of 11 cents per kWh, or can breakeven 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.

In brief, the technical risk and uncertainties in mass and efficiency in developing millimeter wave conversion and beaming remain the main risks to SSP development using the Space Power Grid approach. The Phase I SPG addresses these risks before the 1 GW converters and their ultralight collectors are launched. The Phase I waveguide satellites and the Phase II Girasol mass estimates come in under the previous estimates that we used in SPG architecture, with much reduced uncertainty. Overlapping development of phases I and 2 can greatly reduce deployment time of large scale SSP, but with increased technical risk. The updated architecture presented in IEEE 2012 could achieve breakeven from project start, with a trough of Net Present Value (NPV)
In past work [13], [14] we presented a viability parameter $k$ for SSP, defined as $k = 25000P$. In the mid-1990s, using microwaves to transmit power to ground stations was a common GEO-based SSP architecture, but this has evolved into using lasers [9], [10], [11], with the Earth link system expanded from the relatively low end-to-end efficiency of the system. Prior publications [15], [16], [17], [18], [13]. It proposes an initial exchange of power between terrestrial power plants through space, mainly enabling a day-night power exchange, as well as global reach for all participating power plants. This phase reduces the technical risk of space-based solar power transmission, establishes a global market for power beamed from space, and generates revenue. Gigawatt-level collector and converter satellites are launched into this functional power exchange market. Thus the SPG architecture provides viable solutions for the problems of cost to first power, market acceptance, and reducing the risks in developing high-frequency millimeter wave beam forming and dynamic power transmission using a constellation of satellites.

Through the years various aspects have been explored and solutions developed to various problems. Reference [1] gave an update on these. The most important recent advances in the architecture are:

1. Advancement of a closed Brayton cycle as the mechanism to convert solar power to electricity with very high conversion efficiency. Reference [19] showed that essentially 80 percent conversion to high-frequency AC power can be achieved using a helium cycle to generate mechanical power, and the electrical generator technology of nuclear power plants to convert to electric power. Brayton cycle turbomachines show excellent advantages in specific power as the power level increases, in contrast to photovoltaic systems that offer no better than linear scaling. In other words, large engines achieve much higher power per unit mass than small engines. In addition, the high turbine inlet temperatures and pressure ratios that can be achieved with solar-heated systems in space, enable high thermal efficiency, in turn reducing the mass of the active thermal control system required to radiate the waste heat into space. The net effect is a breakthrough in the specific power of the system, enabling values well above 1.5.

2. Advancement of an aerostat-based ground receiver/ transmitter architecture[20], [21]. Perhaps the biggest objection to the use of the millimeter wave spectrum for power transmission is the high loss encountered when transiting the dense, moist lower atmosphere. Older data from the astronomy community (for instance [22]) show that reception at 2800 m altitude (Mauna Kea Hawaiian islands observatory) is more than 95 percent efficient, in the 200-220 GHz range for dry air. The absorption spectrum is relatively smooth in this region, so that data from slightly different frequencies can

Figure 2. In Phase 2, a 2GW ultralight Mirasol sunlight collector and a 1GW, 220GHz Girasol Brayton cycle converter, in orbits near 2000 km, form the standard component of a Space Solar Power constellation, growing to over 4 TeraWatts of SSP by Year 40. The Earth link system is expanded from Phase 1 with minimal technical risk.

limited to below $3 trillion dollars, at a power selling price of $0.11/kWh. At the ramp rate given in the 2012 paper, SSP could reach above 5.6 TeraWatts by Year 50. In the architecture, the value of the Viability Parameter $k$ is close to unity.

3. Prior Work

Space solar power continues to be a far-off dream because of the extremely high cost of the required infrastructure, and the relatively low end-to-end efficiency of the system. Prior architectures have been described by Arthur C. Clarke [2], Peter Glaser [3], NASA/Department of Energy [3], [4], and the SPS2000 initiative[5], [6], [7], [8]. Most of these assumed that solar power would be converted to direct current electric power by photovoltaic arrays, converted to low-frequency microwaves, and beamed down from geosynchronous earth orbit to very large terrestrial stations. Japanese efforts have evolved from using microwaves to using lasers [9], [10], [11], [12].

In past work [13], [14] we presented a viability parameter $k$ for SSP, defined as $k = 25000P/\eta C$. $P$ 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 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 $k \approx 1$ is where the architecture is reasonably 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. GEO-based SSP architectures using photovoltaic conversion and microwave frequencies, typically project $k$ values less than 0.1, indicating that they are an order of magnitude or more away from being commercially viable.

The Space Power Grid approach has been described in our prior publications [15], [16], [17], [18], [13]. It proposes an initial exchange of power between terrestrial power plants through space, mainly enabling a day-night power exchange, as well as global reach for all participating power plants. This phase reduces the technical risk of space-based solar power transmission, establishes a global market for power beamed from space, and generates revenue. Gigawatt-level collector and converter satellites are launched into this functional power exchange market. Thus the SPG architecture provides viable solutions for the problems of cost to first power, market acceptance, and reducing the risks in developing high-frequency millimeter wave beam forming and dynamic power transmission using a constellation of satellites.

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also be used to gauge losses. Recent work [23] shows that opacity is over 90 percent up to a moisture level of 1.25mm at 275 GHz, and beyond 3mm at 150GHz. The 220 GHz value, which was not examined in this reference, may be expected to be closer to that at 150 GHz than to 275 GHz based on the older broad-spectrum data. In fact at 150 GHz, [23] shows that transmission is above 95 percent up to a moisture level of 2.5mm. Mean moisture level for the winter atmosphere above Mauna Kea is given as 1.68mm of water column. Thus, the problem is the heavy loss due to moisture and denser air below this level, down to sea level. A radical solution to this problem is to place the millimeter wave antennae on lighter-than-air tethered aerostats parked at 4000 meters or more above mean sea level. The 4000m level is quite practical using present-day aerostats and tethers, and it is above the level of most of the moisture even of the monsoons of South Asia, which pose the issue of continuous cloud cover for some months. The tethers would incorporate efficient waveguides. Commercially available waveguides have been found, that offer both the power density and the efficiency to make the lower-atmosphere transit as efficient as the transit between space and 4000m, for which very efficient windows have been identified in the 200 - 220 GHz millimeter wave regime.

Reference [1] addressed concerns raised after the 2011 International Space Development Conference in Huntsville, where experts began to agree that the roadmap to viable SSP had become much clearer. It refined the choices in the SPG parameters, identified some alternative routes towards various related objectives, and reduced uncertainty in prediction. Specific results and conclusions dealt 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 SSP.
6. The need for synergy with terrestrial energy industry to develop SSP, showing that this apparent detour is justified by the long-term cost reduction, early risk reduction, early public acceptance of beamed power through Space, and public support.
7. A much quicker deployment timetable to replace terrestrial fossil power generation with SSP.

### 4. Architecture Update

**Summary of Updates**

In this paper, we present the following advances to what we showed in [1]:

1. Improved orbital calculations for the Mirasol-Girasol link. The Mirasol is now brought down to reduce the distance between the Mirasol and Girasol, in order to overcome the solar beam divergence and spot size problem without major optical system complexity.
2. The heater design for the primary solar heat absorption is improved.
3. The design of the radiator for the closed helium Brayton cycle is improved, using graphene sheets.
4. The effect of a lighter-than-air platform system to receive and transmit the power, with waveguides transmitting it through the lower atmosphere, is considered.
5. The component mass estimates for the SPG architecture are compared with those developed for other SSP concepts by other teams, and this is used to justify the large improvement that we show.

#### Phase 1

The Phase 1 waveguide satellites shown in Figure 3 have not been updated since last year. It has been suggested that using these satellites as mirrors to redirect millimeter wave beams, rather than use antennae and waveguides, might be feasible. In addition, the graphene-based radiator designs presented under the Girasol section may offer advantages. Both of the above would be useful to reduce the satellite mass below the present 3800kg estimates, but since the present mass estimate is already quite adequate to project a viable Phase 1 commercial model, these are not of high priority at present.

**Millimeter wave generation and beaming**

Millimeter wave generation from high-frequency alternating currents poses uncertainties because there have not been civilian applications requiring high power and low weight in this frequency regime. Amplifier efficiencies over 90 percent are projected, but the specific power (power per unit mass) is not established since most published applications to-date are for microdevices where there is large overhead. 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 [24].
Phase 2: Mirasol orbits and design

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 initially conceptualized 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 5.6 TWe of Space Solar Power, over 5600 Girasols and 5600 Mirasols would be needed, with some additional Mirasols for night-area coverage of the Girasols.

The Mirasol large-area sunlight collectors have been moved from the prior 20000 km orbits down close to 2000 km orbit heights. This change removes the need for complex optical designs to bring down the spot size and improve the capture effectiveness of the Girasol concentrator/converter satellites. In particular, it reduces the size of the Mirasols, since the loss of sunlight due to spillage is reduced. The Mirasols are now proposed as ultralight sunlight collectors consisting of 960 pieces each with its own actuator, reducing the amount of mirror turning needed as the satellite focuses sunlight on one Girasol after another. The low orbit implies faster rate of redirection of the beam. The number of Mirasols has to be increased to provide night-side coverage. Some of the cost increase to deploy more satellites is compensated by the decrease in launch cost compared to the 20,000 km orbit locations used before.

Although the large-area ultralight Mirasol collectors are in orbits not far from those of the 1-GW Girasol converter craft, they are kept physically separate because of the need for each Mirasol to switch between Girasols based on the direction and availability of sunlight. By making the Mirasols larger than needed to supply a single Girasol, the number of Mirasols needed can be reduced, even with the shadow/night problem associated with the lower orbit. The aerial density requirement of the Mirasols to meet the mass allowance in the system mass budget, is shown in Figure 4. The design point has an aerial density of 0.06kg per square meter.

The Mirasols also require substantial propulsion fuel to correct their orbits for the effects of solar radiation pressure. Figure 5 shows the effect of solar radiation pressure on these ultralight craft, and the propulsion requirement associated with it.

The Girasol designs have been detailed more in the present paper. The heater section is now seen to be designed from Hafnium Carbide tubes to absorb the solar heating and take the helium working fluid to over 3600K. The first stage turbine blades are also expected to be designed from Hafnium Carbide. Thin graphene sheets with their extremely high thermal conductivity, temperature resistance and transparency, are proposed to form the outer window for the sunlight to enter the pressurized heater section.

5. Assumptions and Parameter Choices

In Table 1 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 5.6 Terawatts of installed SSP. Some parameters change between Phase 1 and Phase 2-3. These data are reproduced from [1]. 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 launch operations become routine and use runway-based launchers.

6. 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, 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, and from DC to microwave beamed power with roughly 80% efficiency [25]. We assume 40% efficiency with 220GHz conversion. Direct conversion using optical antennae, perhaps made of nanofibers [26] 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 frequency 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 are projected to 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 [27].
7. B8: Aerial density of 3 to 7 grams per square meter are cited for solar sail craft [28]. Mass including support structures is much smaller than the value that we have assumed.
8. B9: A 5% allowance for other systems is conservative 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.

### Table 1. 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>
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<td>B17</td>
</tr>
<tr>
<td>Distance between satellites (km)</td>
<td>2400</td>
<td>B18</td>
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<tr>
<td>Power transmitted (design, MW)</td>
<td>60</td>
<td>B19</td>
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<tr>
<td>Phase 2 collector diameter, m</td>
<td>300</td>
<td>B20</td>
</tr>
<tr>
<td>Cooling system kg/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>1000</td>
<td>B25</td>
</tr>
<tr>
<td>Ground facilities development $M</td>
<td>1000</td>
<td>B26</td>
</tr>
<tr>
<td>$M cost per ground facility cost</td>
<td>25</td>
<td>B27</td>
</tr>
<tr>
<td>$ per kw to produce power, ground</td>
<td>0.04</td>
<td>B28</td>
</tr>
<tr>
<td>Sales price, $ per KWh, Phase 1</td>
<td>0.17</td>
<td>B29</td>
</tr>
<tr>
<td>Number of stations participating</td>
<td>250</td>
<td>B30</td>
</tr>
<tr>
<td>MW average per plant</td>
<td>60</td>
<td>B31</td>
</tr>
<tr>
<td>Assumed Discount Rate, percent</td>
<td>6%</td>
<td>B32</td>
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<tr>
<td>Desired Return on Investment, Ph1 %</td>
<td>6%</td>
<td>B33</td>
</tr>
<tr>
<td>Desired Return on Investment, Ph2 %</td>
<td>5%</td>
<td>B34</td>
</tr>
<tr>
<td>Loan percentage, Phase 1</td>
<td>30%</td>
<td>B35</td>
</tr>
<tr>
<td>Loan percentage, Phases 2 and 3</td>
<td>30%</td>
<td>B36</td>
</tr>
<tr>
<td>Sales price, $ per KWh, Phase 3 SSP</td>
<td>0.11-0.15</td>
<td>B37</td>
</tr>
</tbody>
</table>

11. B12: The Phase 1 SPG satellite is conceptualized as transmitting and receiving antennae connected through waveguides, with minimal internal dissipation. This drives thermal management system mass. For a narrow-band tuned antenna and waveguides, 1% loss may be conservative. The waveguides now specified, which are capable of handling a broader range of millimeter waves, achieve considerably better than that transmission at 220 GHz.
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. [27]
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 receiver or a need for larger receivers.
18. B19: Because revenue comes from transacted power, there is a lower limit on the power transacted per satellite, for economic viability. This limit may be down near 10MW. The 60MW level is chosen because the intensities of beams at the ground and at the spacecraft are still kept moderate.
19. B20: Collector diameter is set to 300m arbitrarily.
20. B21: Cooling system mass: The assumed level is roughly half of that on an existing spacecraft. Note that with the Phase 1 satellites and Girasols, total system mass is used directly from the papers on their conceptual design, in the relevant architecture cases. Refer to those papers for details.
21. B22: Launch cost to LEO is assumed at reasonable minimum achievable value for the near term in Phase 1, and at a value projected by SSP proponents for the long-term, to be consistent with other SSP architecture projections.
22. B23: Transfer from LEO to final orbits, and orbit corrections, are assumed to use Krypton thrusters and the required delta-v is doubled from the Hohmann transfer level to account for the continuous low-thrust mode.
24. B25: An allowance of 1000Kg provides for miscellaneous sensors and systems on each Phase 1 craft.
25. B26: $1B development cost assumed, for the technology and procedures to exchange beamed power with satellites. The number of ground stations is assumed to be twice the number of Phase 1 and Phase 2 satellites.
26. B27: In addition, a $25M cost is assigned to each ground facility to install equipment to interact with SPG.
27. B28: Typical US utility power production cost $0.04 per KWH.
28. B29: Assume that Phase 1 SPG power will be sold at 17 cents per KWH. Customers at solar plants will find this reasonable because it saves the immense costs of installing auxiliary generation equipment.
29. B30 and 31: The SPG part of the ground facilities are attuned to the parameters of the satellites.
30. B32: 6% discount rate on financing needed for the SPG, given low interest rates prevailing today, and given that the massive investment needed for Phase 2 SPG can only come through international collaboration and central banks.
Table 2. Mirasol Concentrator Array Design Parameters

<table>
<thead>
<tr>
<th>Element</th>
<th>Mass (kg)</th>
<th>% of Girasol</th>
<th>% of Satellite</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collector</td>
<td>30,000</td>
<td>5.21</td>
<td>4.49</td>
</tr>
<tr>
<td>Cooling System</td>
<td>160,000</td>
<td>27.79</td>
<td>23.96</td>
</tr>
<tr>
<td>Brayton Cycle</td>
<td>20,000</td>
<td>3.47</td>
<td>2.99</td>
</tr>
<tr>
<td>AC generator</td>
<td>50,000</td>
<td>8.68</td>
<td>7.49</td>
</tr>
<tr>
<td>Cryogenics</td>
<td>20,000</td>
<td>3.47</td>
<td>2.99</td>
</tr>
<tr>
<td>220GHz Amp</td>
<td>17,000</td>
<td>2.95</td>
<td>2.55</td>
</tr>
<tr>
<td>Antennae</td>
<td>20,000</td>
<td>3.47</td>
<td>2.99</td>
</tr>
<tr>
<td>Propulsion</td>
<td>170,300</td>
<td>29.58</td>
<td>25.50</td>
</tr>
<tr>
<td>Misc.</td>
<td>30,930</td>
<td>5.37</td>
<td>4.63</td>
</tr>
<tr>
<td>Structure</td>
<td>58,470</td>
<td>10.00</td>
<td>8.62</td>
</tr>
<tr>
<td>Total Girasol</td>
<td>584,700</td>
<td>100.00</td>
<td>86.22</td>
</tr>
<tr>
<td>Total Mirasol</td>
<td>92,000</td>
<td>13.78</td>
<td></td>
</tr>
<tr>
<td>Total Mass</td>
<td>676,700</td>
<td>100.00</td>
<td></td>
</tr>
</tbody>
</table>

Table 3. Mass budget for 1 GWe Space Solar Power Satellite

7. MASS BUDGET COMPARISON

Mirasol

A table summarizing parameters for the Mirasol concentrator array is shown in Table 2.

Girasol

A mass summary for the different subsystems is shown in Table 3. This system mass summary reflects refined estimates of the spacecraft cooling system and the Mirasol optical system mass calculations, as these systems have been investigated in further detail.

8. COMPARISON WITH OTHER ARCHITECTURES

Table 4 attempts to answer the sanity-check question of why we are getting specific power values so much higher than previous SSP architecture proposals, and accordingly so much lower costs. We are exchanging the impossibility of GEO-based microwave architectures, for the technical risk in developing millimeter wave conversion and beamng systems in the near future. We maintain that this is an acceptable risk.

The table uses results given in the detailed architecture study conducted by Penn and Law [29], giving the mass budgets for the various components of each proposed SSP architecture. We see from that comparison that the antenna mass scales approximately in inverse proportion to frequency. Since the frequency of the SPG architecture is 220 GHz compared to the 2.4 GHz of previous proposals, there is a 2-order of magnitude reduction in antenna size expected. Not all of this will be realized, since millimeter wave antenna may be expected to have higher mass per unit area than microwave antennae. However, the net result is that antenna mass becomes a minor component of total mass. Next, we see that the Photovoltaic array mass is a dominant component of prior architectures. Brayton cycle turbomachines offer a very strong advantage in power per unit mass as the power level increases, unlike photovoltaic systems that scale linearly in mass with power. Thirdly, with high-temperature, highly intensified solar thermal conversion, the Girasol achieves very high thermal and thermodynamic efficiency of 80 percent, compared to the 20 percent to 25 percent that photovoltaic systems can even aspire to. This means that the collector area for PV systems must be 3 to 4 times as large as what is needed for a Brayton cycle system, for the same converted power. Conversion from mechanical to AC electric power can be achieved with extremely high efficiency as shown by terrestrial nuclear plants, and this efficiency exceeds the DC to AC conversion efficiency of photovoltaic systems. In turn, the low efficiency of photovoltaic systems compared to the Brayton cycle system means that the active thermal control system mass must be up to the task of radiating out 3 to 4 times as much heat in the PV case as in the Brayton cycle Girasol case. The other major component of system mass is the propulsion system, along with orbit-correction fuel. The mass of these scales proportionally to the baseline system mass above, so that they are also much less in the SPG architecture than in the prior architecture proposals. Thus we see that the mass total is easily an order of magnitude less in the SPG architecture than in the previously proposed photovoltaic GEO-based microwave architectures.

A reviewer pointed out that the in-space mass needed for a Girasol-Mirasol pair was not much larger than that of the International Space Station, whose mass is cited as around 450,000kg. Indeed there is no reason why an uninhabited, remotely-controlled ultralight collector satellite and a 1GW converter, adding up to some 650,000kg should be any more massive than that. There is no need for human life-sustaining facilities, or of docking facilities once on-orbit maintenance is perfected, since the major components of the Girasol will be accessible as replaceable modules from outside. The larger issue in SSP is that we will need thousands of these 1GW collector/converter pairs in orbit, to reach the TeraWatt levels needed to replace terrestrial primary power. Looking at the launch vehicle challenges faced by the ISS over the years, it is clear that an early, determined investment in runway-based heavy-lift space access, should be a top priority.

9. ECONOMICS

The assumptions made in the economics calculations are listed above. The work done to refine the designs of the

<table>
<thead>
<tr>
<th>Item</th>
<th>Mirasol Concept</th>
<th>Halo Concept</th>
<th>SPS-Alpha Concept</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optical Elements</td>
<td>6000 optical elements</td>
<td>100 orbiting reflectors</td>
<td>∼5000 reflectors</td>
</tr>
<tr>
<td>Energy Conversion</td>
<td>Solar Thermal</td>
<td>PV</td>
<td>Array</td>
</tr>
<tr>
<td>Power Generation</td>
<td>Mill Wave</td>
<td>Solid State</td>
<td>∼200,000</td>
</tr>
<tr>
<td>Beam Frequency</td>
<td>2200GHz (Mill Wave)</td>
<td>5.8 GHz (Microwave)</td>
<td>2.45 GHz (Microwave)</td>
</tr>
<tr>
<td>Power Level</td>
<td>1 GW</td>
<td>1.2 GW</td>
<td>2 GW</td>
</tr>
<tr>
<td>System Mass</td>
<td>677MT</td>
<td>13,044MT</td>
<td>∼9,350MT</td>
</tr>
</tbody>
</table>

3 types of spacecraft indicates that these assumptions are realistic, and can be satisfied with some research and development as might be expected over the next several years. Reference [1] showed an accelerated ramp rate of the SSP system deployment. The risk in this deployment scheme is that the development for the Girasol/Mirasol system has to be completed before full usage experience from the Phase 1 SPG power exchange system has been obtained. The technical risk in this can be mitigated by early deployment of beaming experiments from the International Space Station, and a multinational power exchange satellite experiment as laid out in [30].

The economics of the system are expressed using Net Present Value, following usual practice. The NPV evolution is shown for phase 1 in Figure 6 and for the full architecture in Figure 7. The positive NPV segment beyond year 12 in Phase 1 is shown because the income from the power exchange will continue, and provides an excellent source of revenue to invest in the deployment of the 1 GW Girasol-Mirasol pairs needed to move towards space-based power generation. There is no possible supply competition for this market segment, to reduce the slope of the positive NPV growth in this period. This illustrates the crucial benefit of having the Phase 1 power exchange, rather than rushing headlong into SSP in competition with other generation technologies. Not only is there a source of development funds, there is also the market assurance that comes from an established power trading system. Beyond Phase 1, the deployment schedule will probably be dictated by the availability of investment funds, and the selling price of power. The figure shows that the NPV trough can be reduced to roughly 2 trillion dollars, turning upwards by Year 25, with a selling price of $0.11 at the wholesale level (these prices are an average of $0.05 below the cost to the end-use residential customer). Clearly the scale of investment needed for full-scale SSP is such that only a global enterprise can undertake this, a fact that reinforces the need for early global buy-in and partnership.

10. IMPLICATIONS FOR RUNWAY-BASED LAUNCHERS

The deployment of Space Solar Power on a scale large enough to make a difference to the world’s energy supply, requires a major investment in space launch technology and infrastructure. To deploy 1 Terawatt of power supply from orbit, at a specific power of 1.5 kW/kg, requires a minimum of 0.67 billion kg in orbit. Thus, assuming heavy-lift launchers carrying as much as 100,000 kg per launch, the proposed 5.6 TW of SSP installation will require 37520 launches, even without all the launches needed for related purposes. To achieve this in 40 years, over 5 launches every 2 days will be required around the year 40. We assume, as do all others who attempt to develop SSP architectures, that launch costs will come down from today’s level, if SSP is to ever happen. However, we see little prospect of pure rockets becoming inexpensive enough. The reason can be seen by considering the cost breakdown of a typical space launch operation. Very little of the cost is the cost of the material expended as the vehicle or the propellant. Heavy-lift rocket launchers are massive vertical objects, which must be transported very slowly to the launch pad and tested extensively for each launch, as they are not recovered. The cost of ensuring safe operation, involving hundreds or thousands of
employees and extensive testing of each vehicle, dominates launch cost, and the series of steps needed for each launch precludes much greater launch productivity than is currently seen.

To make space launch operations routine and frequent, the operation must be brought to an airline-level of repetitiveness and efficiency. This means runway-based launchers that can take off and land horizontally. In turn, this implies air-breathing propulsion for the atmospheric section of the flight, probably with recapture of oxygen by liquefying air on the way up. Development of horizontal takeoff and landing space launchers is hindered by the lack of demand for space launch. In turn, SSP cannot be deployed without such a capacity. In the final paper a section will be added on the development of runway-based launchers, with estimates of the payload, development cost, number of launching stations, types and number of launchers needed, frequency of launches, and types of payloads.

11. SUMMARY OF NEEDED RESEARCH AND DEVELOPMENT

Several items remain as essential technology development. These are briefly enumerated below.

1. Millimeter wave conversion to and from alternating current, continues to be a first-order uncertainty in its efficiency and specific power when applied on a multi-megawatt scale.
2. Runway-based space launch, especially airbreathing vehicles with liquid air cooled engines.
3. High-temperature materials such as Hafnium Carbide, and their performance for applications such as that in the blades of the first turbine stage.

12. CONCLUSIONS

1. The specific power for the space-based component of the Space Power Grid architecture for SSP now promises to be above 1.5 kW/kg
2. Millimeter wave dynamic beaming from 2000 km orbits is seen to provide the expected reduction in system mass over architectures with GEO-based microwave beaming.
3. The use of a solar Brayton cycle provides the remaining improvement in specific power, due to the favorable scaling of turbomachine system mass with increasing power compared to the linear scaling of photovoltaic architectures.
4. Bringing down the Mirasol solar collectors to 2000 km orbits enables better capture of the solar power using the Girasol concentrators.
5. The specific power can be further improved using graphene-based radiators.
6. The mass budgets specified in the 2011 version of the SPG architecture are shown to be reachable.

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REFERENCES


