Near-Millimeter Wave Issues for a Space Power Grid

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Abstract This paper reports continuing work on an evolutionary revenue-generating approach to Space Solar Power. The 220 GHz atmospheric transmission window is chosen, leaving open the option of using millimeter wave or laser wavelengths. The progression from frequency to system business case is laid out, seeking the performance figures needed for a self-sustaining system and to open up Space Solar Power in 15 to 17 years from first launch. An overall transmission efficiency in excess of 30 percent is required, from DC to beamed power and back to DC or high-voltage AC, to meet a delivered free-market price target of 30 cents per KWH, or 20 percent if a price of 45 cents per KWH. Climate data show that rain obscuration is a non-issue for many of the renewable-power sites that comprise the market. The technology of direct solar conversion to DC and to beamed power would satisfy the needed efficiencies but requires advances in nano-scale fabrication with dielectrics.

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INTRODUCTION

This paper reports continuing work on an evolutionary revenue-generating approach to Space Solar Power. The concept calls for a 3-phase deployment. In Phase 1, a constellation of satellites in low to mid earth orbit serve only as receivers and waveguides to beam microwave power between transmitters and receivers on Earth. This phase enables renewable power plants to be built at remote locations, and yet exploit the temporal and geographic differences in cost and demand for power, while being able to get good prices for the power generated when the sun is brightest or the wind is strongest. Real-time beaming also allows these plants to smooth out their power output using input from plants as far away as the other side of the globe, and achieve "baseload" plant status without having to set up costly auxiliary fossil-fueled generators. They can thus command better local prices for their output. This establishes the infrastructure and market. In Phase 2, replacement satellites deployed 10 to 17 years after the first satellites incorporate collectors and converters to generate beamed microwaves from concentrated solar power, feeding into the established space power grid at lower costs. In Phase 3, large areas of ultra light collectors in high orbits focus visible sunlight on to the collector-converters in lower orbits. The business case is based on 4 features:

1) Enabling development of new solar and wind power plants by boosting their competiveness. The carbon credits earned as a result also provide a small continuing revenue stream. They also qualify these plants for larger public investment.
2) The use of a growing constellation of L/MEO satellites vastly reduces antenna size and beam width, eliminates the need for major assembly in orbit, and thus minimizes development and launch costs.
3) Early revenue growth with a few satellites and participating plants, eliminating the huge cost-to-first-power obstacle of GEO-based concepts. Constellation growth is matched to the commissioning of renewable power plants, thus reducing lag between investment and revenue generation.
4) Minimizing the impact of weather by providing different alternatives for power transmission to the ground-based grid.

The thrust of our effort is to develop a comprehensive model that projects realistic efficiency and cost figures for the expected time of deployment, and relates parameter choices to the final business case.

Boechler (2006) estimated the end-to-end efficiency achievable in the short term and the long term, concluding that near-term efficiency would be no better than half that of the present terrestrial grid in urban areas, but long term efficiency, with direct power conversion from broadband solar power to beamed narrowband power using optical rectennae would match or exceed that of the terrestrial grid. The higher short-term cost would be quite acceptable in view of the large variation in cost and production rate of power at different locations. In a follow-on paper at the IAF 2006 (Komerath, 2006), we postulated a system based on transmission frequency in the 200GHz regime and a constellation of 36 sun-synchronous satellites at 800km altitude. Efficiencies in this regime are not at the levels achieved in the 2.4 GHz regime. However, there is reason for optimism, given advances in millimeter-wave technology for other applications, that the efficiency can be improved. The cost and revenue aspects of the system were estimated at a zeroth-order level, and the results suggested that the system could be developed to the full SSP stage within 30 years at a reasonable level of public investment if the conversion efficiency became acceptable. In a recent paper at the AIAA Space 2008 conference (Komerath, 2008), we compared the economics of approaches using different frequencies and choices of orbits. It is seen that approaches using frequencies lower than 100 GHz are not viable, confirming the pessimism of those who have been struggling with traditional SSP concept for decades. However, it is not necessary to go to the laser regime either. It is also seen that a combination of near-equatorial, polar and elliptic orbits could offer the necessary features of long transmission times from power plants, and retail power delivery all over the world.

The 200 GHz regime was considered in (and is probably used since) the 1980s and early 90s because it offers strong advantages in propagation through smog and dust clouds, while suffering strong disadvantages in other respects. Recent advances in this regime make it worth re-examining for efficient power exchange with Spacecraft. In addition, the issue of spacecraft heating poses a large design issue, when each power plant may be capable of transmitting and receiving power on the order of 100MW. Even a 1% transmission loss inside the waveguides of the spacecraft presents an unprecedented thermal management problem. In this regime one has to think in terms of conversion to useful work, and beaming at other frequencies, rather than mere heat dissipation.

In this paper, we will report on a further examination of several technical issues as possible given the difficulty of obtaining published data in this regime:

1. Choice of transmission frequency in the 100-250GHz regime
2. Atmospheric transmission windows and weather aspects
3. Possible efficiencies in this regime
4. Choices of orbits

Establishing System Size and Power Level

Komerath (2008) explored the minimum size of the Phase 1 system, required to make it self-sustaining regardless of the implementation of Phases 2 and 3. This is of course a steep requirement, as we have no evidence that the nations of the world would embark on a space-based grid solution to the issues of developing renewable energy plants. Such a system would require the motivations that drive Space agencies world wide, and hence must have SSP as an ultimate goal. However, the exercise established the cost of power, the required end-to-end efficiency, and the relations to satellite number, and the minimum level of power transacted per satellite to make the system viable. The exercise was driven by the need to bring the power level per satellite as low as possible, since the thermal load on the satellite was driving the project cost. It also explored how much impact public funding in the initial stages would have on the economic viability of the project at the selected power level.

The procedure to relate frequency choice to system economic viability is given below. The values used are illustrative, not optimized, except for the choice of the 220GHz value based on the known atmospheric transmission window. The choice of the high frequency, as stated before, allows the design of antennae to capture essentially the whole beam (>99% beam capture), thus eliminating the only part of the transmission loss that can be eliminated.

Two lower limits on antenna size carried on a spacecraft are (a) the intensity that can be handled, and (b) the satellite-to-satellite beaming requirement. The distances involved in (b) are large, and both receiver and transmitter must be the same size. The space-space antennae may thus be considerably larger than the space-earth antennae on satellites, until the number of satellites and power plants becomes large enough to provide enough intermediate relays and shorter transmission distances.

The orbit height is selected based on the period and the time for which each satellite can be seen within an azimuth cone of half-angle 45 degrees. The choice of 45 degrees is partly because atmospheric transmission data exist down to this angle, and the losses are relatively low. Keeping this "access time" at a reasonable value (to reduce switching transients and related costs), gives a height of roughly 2000km. In practice one may choose a sun-synchronous orbit at some nearby altitude, or go to lower altitudes if the number of satellites becomes larger and switching becomes a non-issue. The lower limit is where atmospheric transmission losses may be encountered in satellite-to-satellite beaming; however the time-above-station limit is expected to be more stringent until the constellation grows to a large number.

Antenna size and orbit choice are related through the standard formula for complete beam capture

$$D_r D_t \big/ \lambda S = 2.44$$

where D is effective antenna diameter, subscripts t and r denote transmitter and receiver, lambda is wavelength and S is the distance between the transmitter and receiver. The 45-degree transmission distance is taken as the design value. For a 50m antenna in space, a 200m diameter antenna on the ground is selected. Each satellite spends 9.76 minutes within the beaming cone from a ground station at sea level. While this decreases for high altitude stations, we assume that the cone can be widened substantially with no penalty in the thinner atmosphere.

For inter-satellite beaming, two satellites separated by 45 degrees in circular orbit were considered, giving a transmission distance of over 6400 kilometers. Each antenna was 146 meters in effective diameter, and each craft had two such antennae in addition to the ground beaming antenna. A mass per unit area of 0.05kg/m^2 was assumed for the antennae. Cooling system mass was assumed at 1500kg per 2.5MW, based on jet engine figures. This is highly conservative since spacecraft turbomachine systems achieve much higher power per unit mass. The mass of fluid (assumed water vapor) needed for a 400K temperature rise in 60 seconds was obtained. A 1000kg miscellaneous systems mass completed the satellite dry mass, with an added 30% propellant mass for orbit correction and 10% margin, to get a launch mass of 4500kg.

Given the dry mass and a chosen number of satellites, the development and production costs were estimated using the NASA-Air force NAFCOM cost models with an 85 percent Wright Learning assumed. Launch costs were estimated using an interpolated form of the lower-bound estimates from the FUTRON launch cost survey of 2004 that is based on data up to 2000. This gives $4,300 per kg to circular orbits at 2000 km altitude, giving a launch cost of $19.4M per satellite. An Operations cost is computed from the NAFCOM based on the number of satellites in operation at any given time, assuming that the SPG is closest in operating nature to a communications/navigation satellite constellation. Given the nature of the datasets on which these are based, we believe that the estimates are quite conservative for the SPG system.

The results are shown in Table 1. The minimum power level could not be brought much below 60 MW per satellite. At this level, the system would start functioning with as few as six satellites and 12 power stations, but was then expanded to a size of over 100 satellites and stations. The number of stations can be considerably larger than the number of satellites, when intermittency of transmission and weather issues are taken into account, and the cost of installing beaming and receiving facilities on a ground station are small in this architecture.

The assumption in the above that cannot be defended at present is that an end-to-end transmission efficiency of 30% can be achieved from and to the equivalent of ready-to-transmit grid-based AC power, including the conversions to and from beamed power at 220GHz, and the transmission through the atmosphere and satellites. This is not as bad as it looks. First, the power that is transacted is usually from peak generation times at renewable plants, so that its marginal cost of generation is small (without the SPG or large storage, this would go waste), and the $0.04/KWh production cost is liberal. The price of power at the delivered end is held down to $0.30. If the efficiency were reduced to 0.2 (i.e., only 20 percent of the generated power reaches the receiver plant), the price would have to be $0.45, which may be acceptable for initial uses of the Space Power Grid to remote locations or peak usage times in cities.

TABLE 1. Present System Parameters

Parameter	Value
Satellite Power Level	60MW
Satellite mass	4510 kg
Launch cost to 2000 km high circular orbit	$ 19.8M
Development cost for system	$ 330M
Production cost for 1st 36 satellites	$1370M
Ground facilities development cost	$1000M
Per satellite annual mission operations and data analysis cost	$2.75M
Ground station power level:	$55MW
Cost of production of power:	$0.04 per KWH
End-to-end efficiency of beaming power grid	0.3
Sales price at delivery point	$0.3 per KWH
Gross margin	$0.05 per KWH
SPG share of gross margin:	$0.045 per KWH

Orbits and Transmission Scenarios

Scenario 1, Near-equator plants and receivers. The orbit height of 2000 km gives an access time within the 45-degree cone, of 7 to 10 minutes at ground stations. Several types of orbits can be considered. For stations near the equator, the first several satellites are best placed in orbits near the equator. Thus a system start-up with as few as 6 satellites and 12 plants can be considered, as has been done above.

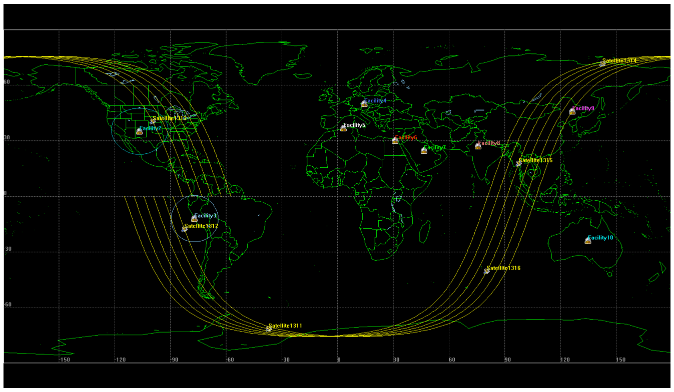

Figure 1: Ground Tracks of 6 sun-synchronous satellites at 1900 km height

Scenario 2 is the Afternoon Sun system. The peak demand as well as peak solar power output occur during the afternoon hours in summer. So access for about two hours in the afternoon may be the most important feature for supplier solar plants, located in many parts of the world. This can be achieved using a few satellites in sun-synchronous orbits. As orbit height is varied from 720km to 2000 km, the access time from a given ground station for a system of 6 satellites, varies from 15 minutes per 24 hours to roughly 90 minutes per 24 hours, within a 45-degree half-cone of visibility from each station. An orbit height of 1900 km for sun-synchronous orbits gives roughly 80 minutes of access per 24 hours. This orbit performs 23 revolutions around the earth every 48 hours. The ground tracks for one orbit each of the 6 satellites for this orbit are shown in Fig. 1. Scenario 3 is High Latitude, Burst-Mode Transmission: The difficulty with sun-synchronous orbits is that each ground station can only see one orbit on a given day, although the satellite completes as many as 11.5 orbits per 24 hours. At higher latitudes, the spacing between successive ground tracks of a sun-synchronous satellite, become closer, and a given ground station can see two successive orbits of the same satellite, separated by about 125 minutes. However, each will only be seen for a short duration. Thus burst-mode transmission for a few seconds (up to 2 minutes at 60 degree latitude, more at higher latitudes) may be repeated at regular intervals essentially through each day and night, with only a few satellites. Scenario 4 is the Steady State Phase 1 SPG. As the number of satellites rises, sun-synchronous orbits become viable for continuous transmission. For the 1900km sun-synchronous orbit, the number necessary for continuous transmissions is 72 satellites, which is well below the expected number of satellites in an established SPG system.

Generation and Atmospheric Transmission In The 200-250GHz Regime

Table 2 is constructed from Theissing (1956) reported in (Anon, 1997) for total attenuation through the atmosphere, for transmission at 45 degrees azimuth, the limiting value in our system calculations. The point is that transmission loss is about twice, but only about twice, that in the low frequency regime. The models that we have been able to find are interpolated across frequencies; however there are experimental values at 220GHz and 140GHz. Falcone (1982) presents a model for atmospheric attenuation in the 30 to 300 GHz region. In this range, water vapor has resonances at 22GHz and 183 GHZ, while oxygen has several resonant lines around 60GHz and a single line at 118 GHz, but also affects transmission at other wavelengths in between. They use a Mie scattering model for fog and rain. Large discrepancies were found with experimental data from about 25 sources that required adjustment with empirical factors for the 15-60GHz and the 60-300GHz regimes. The results from Barrett (1962) and Gaut (1968) for water vapor, and Meeks (1963) for oxygen were used, since the empirically corrected model came close to these.

The effect of clouds, fog and rain are to scatter the radiation, and to absorb it in dielectric heating. Calculations were presented for 1km horizontal transmission through clear 1 atmosphere air at 20 deg. C and through fog of various densities. One effect of the fog and rain is that the frequency windows of higher transmission get obscured. It should be noted that in this regime, transmission using anything other than low-frequency microwave (below 10GHz) is impractical. In this context, the SPG approach offers a partial solution. Dense cloud cover is usually limited to the approach and duration of storms. Heavy thunderstorms are limited in coverage area and duration. Weather fronts are a few hundred miles deep at most. So in most cases of transmission to grid-connected locations, alternative beaming locations can be found within a few miles, at most times. Where this is not feasible, additional storage appears to be the only option.

TABLE 2: 1-way atmospheric Attenuation of Micro and millimeter waves at 45 degrees azimuth (Anon, 1997).

Frequency	220GHz	140GHz
Dry atmosphere	0.8dB (17%)	0.8dB (17%)
Medium humidity	3dB (50%)	1.0dB (20%)
High humidity	4.6dB (65%)	1.4dB (28%)

Candidate locations

The most powerful beam is the one rising from a power station, and hence it makes sense to locate these in areas where clear dry skies are prevalent. This matches the characteristics of the ideal locations for solar and wind plants – high plateaux and mountain ridges for example. The probability of rain at given levels has been studied in Anon (1997). In the regions including much of southern California, the plains of Nevada, Arizona Utah, New Mexico, central and west Texas, Oklahoma, Colorado and the Dakotas, more than 8420 hours per year have essentially zero rainfall. These are the ideal regions for the generation of solar and wind power, and the regions where the terrestrial grid is sparse..

Efficiency

Early public-domain literature on high power millimeter wave beaming comes from Rostoker (1988). Hoffert (1988) advanced the idea of beaming microwave power to satellites, in order to provide housekeeping, orbit maneuvering and burst mode power to defensive satellite constellations. They saw this as an alternative to nuclear or other sources in orbit, and suggested some form of chemical energy storage on the satellites. Beamed power levels on the order of 100KW were envisaged for durations of hours, with burst mode power upto 1GW for tens of seconds, repeated with repetition times of 100 seconds. For microwave frequencies in the 10 - 40GHz regime, upto 65% conversion efficiency was projected, using magnetrons, but the antenna size and attendant satellite mass appears to have limited the choice of frequency to 2.45 GHz. Atmospheric transmission at angles up to and beyond 45 degrees was calculated to entail insignificant penalties as long as the antenna size could be kept large enough relative to the wavelength. The fuel cell storage system was estimated at around 2000-4000 Kg, at a power density of 10KW per kg. Although sources in the 140 to 300 GHz regime were seen to have various applications, the efficiency figures reported for their generation were generally very low, on the order of 1 to 7 percent. For high pulsed powers ranging to Terawatts, gyratron sources were the best option.

In the SPG, the choice of high frequencies enables antennas sized to capture essentially the entire beam. JAXA has reported antennae designed for 99.93 percent beam capture, with frequencies below 10GHz. The same can be achieved with much smaller antenna size in the 200GHz regime. We thus select 0.999 as the antenna capture factor. Waveguide efficiency is a major concern, because beams have to be turned through 90 degrees or more in a compact space, and any loss results in internal satellite heating, demanding an active cooling system. Being a new application, we assume that 1% loss occurs in the waveguide. Thus the combined antenna-waveguide factor is 0.993x0.99. There is some argument for a vacuum space waveguide between antennae but it is not clear how to implement it with an acceptable spacecraft configuration.

To-date, the published figures on efficiency of generating millimeter wave beams from electricity, are dismally low, the highest we have found being 7%. Clearly, this is far below the acceptable level for use as a transmission system. However, there is reason to pursue the millimeter wave regime for the following reasons:

1. Up to 39 % efficiency has been demonstrated for conversion from broadband sunlight to 1064nm laser beams, using Nd-fiber lasers doped with Chromium, in experiments by Saiki (2006).
2. The space system sized on millimeter-waves results in larger and more massive components than a system designed around 1064nm beams, and hence the mm wave system design presents an upper bound for system costs as well.
3. Rule-of-thumb technology estimation gives us the result that conversion efficiencies in the lower-frequency microwave and millimeter wave regime must be larger than that in the visible laser regime.
4. In the past few decades, interest in high-power millimeter wave beam sources has been limited to the beam weapon community and the fusion power community, both of which are generally inaccessible from the open literature. While solid state electronics has shown considerable interest in the atmospheric transmission windows at 140Hz and 220Hz, the interest has been mostly in beaming information signals and not high power, so the generation efficiency has not been a driving criterion. For high power, the preferred (published) sources still appear to favor gyratrons.
5. The issue of directly converting broadband sunlight to narrow-band millimeter wave beams has not received much attention. The technology of optical rectennae promises devices that can bypass the DC conversion step and perhaps offer lightweight devices that offer very high conversion efficiencies (80+ percent). There is no fundamental reason seen, why this cannot work at least as well in the longer mm wave regime than it can in the visible regime.

Goswami (2004) reviewed the technologies for conversion of sunlight to DC without going through solar cells based on the work of Bailey (1972) and Fletcher and Bailey (1973). This work uses the idea that sunlight can be treated as a spectrum of electromagnetic waves and hence captured nearly completely using an antenna that accommodates the smallest wavelength and all of its Fourier harmonics. Thus the technology is limited by the fabrication capability of antennae in the micrometer (visible regime) down to the nanometer (UV) range. Farber (1988) tried some experiments at 100GHz but the results were not unambiguous. Lin (1996) observed what may be resonant light absorption by a nanostructure, leading to a short circuit current. The experiments of Brown (1984) showed up to 84% conversion from beamed microwave at 2.45GHz to DC, with a power level of 30KW. Further experiments on rectenna efficiency at upto 35GHz have been limited by the characteristics of the diodes used. Yamazaki (1988) showed that biological antennae using algae can absorb energy at 620 and 560nm, and may turn out to be more efficient in the near term than artificially manufactured antennae, but this poses no way of converting to DC. Goswami (2004) point out those dielectrics that must be used at high frequencies to avoid the losses in media such as metals, and point to several design approaches. The "distributed parameter power rectifier" proposed by Ishii (1991) is for converting 1-30THz waves from a Tokamak fusion reactor to DC. Grober (1997) demonstrated an optical probe with transmission efficiency approaching unity using near-field optics. Application to the far field case or for visible wavelengths is unknown.

None of the above offers any near-term assurance of a viable system for space solar power. However, direct power conversion, where the DC step is entirely bypassed and broad-band power captured by an antenna is beamed back out as a narrow-band millimeter wave beam, is a game-changer. This keeps this technology as a serious contender given that its deployment need only occur 15 to 17 years after the first stage Space Power Grid is deployed. The implications are that the efficiency of conversion can be in the 85 to 100% range (Berland, 2003), with a power density of 1.165KW/m^2. Even at an antenna mass of 0.25kg per m^2, this give a specific power of 4.658KW/kg, 3 orders of magnitude above today's PV systems. Concentrating the broadband solar power using the high-orbit ultra light collectors allows the most efficient use of the converter mass.

Thermal management on the satellites was cited by some reviewers as a showstopper when the Space Power Grid was first proposed to the NASA Institute of Advanced Concepts a few years ago (at much higher power levels per satellite) but now it is seen to be well within the reach of efforts ongoing in the space community, and is hence not further considered here. The thermal system mass, even at conservative estimates, is not a limiter any more to the spacecraft mass. It is assumed that SPG satellites will use some type of closed system heat engine, and convert a substantial part of the "waste" heat to retail useful power, perhaps at frequencies more suited to space applications, and generating higher revenue. Technologies for this have been demonstrated already.

CONCLUSION

The technical challenges in implementing the Space Power Grid approach to space solar power are considered in this paper. From prior work we show how to systematically link technical choices of frequency and orbit height, to the system economics, enough to see what is needed in order to make a viable, self-sustaining and growing system. This opens up Space Solar Power in about 15 to 17 years from the first launches. Revenue generation starts with the first launch, which can occur in about 6 years, using the unique window of opportunity posed by the drive towards renewable power plants and the policy urgency of Global Warming. The unique market niches that can be served by SPG eliminate the need to compete with the terrestrial grid until the flow of power from space solar generation becomes substantial.

While today's technology level is insufficient to bring the cost of power below the level where SPG can compete with well-developed terrestrial power grids and fossil plants, Direct Conversion technologies offer strong promise of breaking through this barrier. In the SPG, this can be deferred 15 to 17 years from successful commencement of the Power Grid phase, thus greatly decreasing risk and increasing motivation. A systematic progression from technical choices based on antenna laws and atmospheric windows is used to estimate the minimum size and number of the satellites in the power grid phase, for a self-sustaining system based only on power transactions. Given this baseline configuration, the challenges are quantified.

1. Overall transmission efficiency in excess of 30 percent is required, from DC to beamed power and back to DC or high-voltage AC, in order to meet a delivered price target of $0.3 per KWH, based on current free-market numbers. However, this decreases to 20 percent if a price of $0.45/KWH is sustainable for initial applications, or if large public funding goes into system development and initial operations.
2. To minimize transmission losses, the antennae must be designed for near 100% beam capture. The frequency used for the space-to-space transmission should thus be in the 100 - 250GHz range. Unless there is an efficient way to convert between this regime and the low-frequency 2.4GHz regime, this consideration dictates the use of the same frequency for the atmospheric transmission segment. The choice is down to the two windows at 140 or 220 GHz.
3. The system design based on 220GHz provides an upper bound for satellite size compared to laser wavelengths; hence the SPG system is conceptually compatible with the choice of laser wavelengths.
4. Dry air transmission efficiency at 220 GHz is acceptable for transmission angles up to 45 degrees.
5. While rain of any intensity is unacceptable to the system, as for all frequencies above 10GHz, climate studies show that the probability of system interruption due to rain is acceptably low over substantial portions of the United States that encompass the ideal locations for wind and solar generation.

6. Unlike GEO-based approaches, the SPG approach enables easy diversion to clear-weather receiving stations for forwarding through the terrestrial grid to rain-obscured locations.
7. The technology of direct solar conversion to DC and to beamed power, offers game-changing potential, but also requires advances in nano-scale fabrication with dielectrics.
8. Given these advances, the necessary system efficiencies for Space Solar Power can be achieved in an evolutionary manner through the Space Power Grid approach.

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