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A US-India Power Exchange Towards A Space Power Grid

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Abstract— The Space Power Grid (SPG) architecture described in papers from our group since 2006, is an evolutionary approach to realizing the global dream of Space Solar Power (SSP). SPG first concentrates on helping terrestrial power plants become viable, aligning with public policy priorities. It enables a real-time power exchange through Space to help locate new plants at ideal but remote sites, smooth supply fluctuations, reach high-valued markets, and achieve baseload status. With retail cost kept to moderate levels, a constellation grows in 17 years to 100 power relay satellites at 2000 km sun-synchronous and equatorial orbits and 250 terrestrial plants, exchanging beamed power at 220GHz. In another 23 years, power collection satellites replacing the initial constellation will convert sunlight focused from ultralight collectors in high orbits and add it to the beamed power infrastructure, growing SSP to nearly 4 TWe with wholesale and retail delivery. The SPG-based SSP system can break even at a healthy return on investment, modest development funding, and realistic launch costs. The immense launch cost risk in GEO-based SSP architectures is exchanged for the moderate risk in developing efficient millimeter wave technology and dynamic beam pointing in the next decade. A US-India space-based power exchange demonstration would constitute a rational first step towards a global SPG. We discuss two options to achieve near-24-hour power exchange: 1) 4 to 6 satellites at 5500km near-equatorial orbits, with ground stations in the USA, India, Australia and Egypt. 2) 6 satellites in 5500 km orbits, with ground stations only in the US and India.

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1. Introduction

Much of humanity today does not enjoy the $0.10/KWhe, uninterrupted delivery of electric power that is taken for granted in urban industrialized societies. In regions that are not wired for power, residents pay exorbitant costs for a few watts or watt-hours and suffer lack of basic amenities and opportunities. Thus the first point to make is that competing with the efficient, reliable terrestrial utility and power grid, is not the only purpose of a Space-based electric power resource. The ability to reach all parts of the world at any time is a very significant characteristic, beyond being worth a high price. On the other hand, it is entirely possible that the price commanded by terrestrial utilities will keep rising beyond the level where we can make SSP viable even in this market.

In this paper, we will start by pointing out that SSP is an old dream, not a new idea. It has not been realized, because SSP is hard. There is no short-term viable prospect for SSP as a significant source of power except for some very special and high-valued markets. The periodic spikes of media interest in SSP through the past six decades correlate with drives to develop something else, where large scale construction in Space for SSP was advanced as a popular civilian justification. We argue for a strategy where SSP helps, rather than competes, with terrestrial renewable energy initiatives, as a way to establish the technology and the infrastructure to exchange power between markets. In other words, Space is a venue for power exchange rather than just generation, and as such we call our architecture the Space Power Grid (SPG). This approach will also buy time to develop the best technological options for the Gigawatt-level SSP satellites that will replace the first-generation relay satellites. We have shown in recent work that such a strategy can lead to an economically viable infrastructure with a continuing revenue stream. This will help develop the massive satellites needed to expand SSP to the 4 Terawatt level of today's fossil-based primary power supply.

The US-India Strategic Partnership initiative was announced during the tenures of President Clinton and Prime Minister Vajpayee, and expanded under the tenures of Presidents Bush and Obama, and Prime Ministers Vajpayee and Manmohan Singh. This provides a special near-term opportunity to start demonstration experiments leading to the Space Power Grid architecture. The formidable technological obstacles are discussed, but seen to be within reach of focused research.

2. SSP is an Old Dream

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. Several periods of heightened interest in SSP are listed in Table 1, along with major initiatives or policy concerns existing in those periods. The large GEO SSP microwave platform idea is credited to Peter Glaser [2], then a Vice President of the Arthur D. Little Company, renowned for its strategic planning expertise. The massive number of launches required to construct such a platform probably helped to convince the US Congress to fund the Space Shuttle Transportation System, projecting that the launch cost would come down to $100 per lb ($220/kg) in routine, mass production operation. NASA and the DOE studied the concept, with DOE given development responsibility [3,4]. Interest appears to have waned until the 1990s, when the US "Fresh Look" study [5,6,7] and the SPS2000 international initiative involving the International Space Station Partners [8,9,10,11] generated strong interest, with scale models and demonstrators being built in Japan. 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 [12,13,14,15], though only JAXA [16,17] 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 [18,19,20] indicate strong interest from both governments and policy think tanks.

To understand the point of Table 1, one might use the lesson of the 1963 movie "Mouse on the Moon" [21]. Governments may have their own grand and changing aims that cause temporary surges of interest in SSP. It is up to the Mad Professors and expert scientists and enthusiastic students, to use these periods of official interest and make the needed breakthroughs. Once the breakthroughs are identified, governments may get serious about actually going forward to realize the dream of Space Solar Power.

Table 1: Major Studies on SSP, and the Contemporary Policy Issues

Studies	Contemporary Issues
1.Arthur C. Clarke: ET Relays, GEO opportunities: 1945 2.1st artificial satellite, 1950s 3.Peter Glaser (Arthur D. Little Co) GEO SSP architecture: 1968	Beyond Apollo? Case for Space Shuttle: 1000s of launches at $100/lb to LEO
4.NASA/ASEE Space Settlement study, 1977 5. NASA/DOE NASA TM81142, 1979	Beyond SkyLab? STS? ISS?
6. SAIC Fresh Look: NAS3-26565, 1996 7. SPS2000 JAXA/NASA, 1992-present 8. "Gold Rush to LEO" 9. JAXA LEO demo wide-area beaming proposal	SLI/ Heavy Lift? Commercial Launch Moon-Mars
10. India-US SSP Partnership (Garretson, 2010) 11. NSS-Kalam announcement, 2010	Global Warming, Peak Oil, India-US Strategic Partnership, Etc.

3. SSP IS HARD

The 1979 NASA/DOE studies concluded [4] 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. A very simple calculation shows why. The full AM0 (Air Mass Zero) spectrum delivers 1366 watts per square meter [22] of collector area in Earth's orbit in space. With possible future conversion efficiency of 60% to electric power, 90% to a beam reaching Earth's surface with another 10% loss, this means that 1GWe delivered to the terrestrial grid means a collector area of 1.67 square kilometers. Today the possible efficiency is at best half of the above, so that the area per GWe is over 3 square kilometers. Looking at it another way, the ambitious target for the specific power (electric power per unit mass in orbit) of SSP is 1KWe per kg, which implies well over 1 million kilograms in orbit for a 1GWe system. Present architectures promise less than 0.3 KWe/kg, so that a 1GWe SSP craft requires over 3 million kilograms in orbit. The launch cost alone to GEO is over $5000 and probably over $10,000 per kilogram, so that just launch cost exceeds $30B. Viewed another way, a general thumb rule in renewable energy resource development is that the installed cost must approach $1 per watt. Wind plants approach $2 per watt. Contemporary terrestrial photovoltaic (PV) systems cost from $4 to $6 per watt, installed. Just the minimum launch cost of SSP systems is in the range of $15 to $30 per watt, putting them out of competition except for very special applications.

That is only a small part of the cost, since the ground infrastructure for a GEO-based SSP system is massive, dictated by the laws of physics. Figure 1 shows the impact of beaming frequency on the size of the ground infrastructure, even if we size the antennae to receive only 84% of the beam power (main lobe). For a given frequency and beaming distance, the product of the receiver and transmitter diameters is a constant, so values for other choices of the space antenna diameter can be computed easily. With the space antenna diameter set at 150m for millimeter wave and microwaves, and at 10m for lasers, the ground receiver diameter increases with orbit height. Figure 1 shows that frequencies above 100 GHz are needed for any realistic ground antenna size. Even then, GEO is a very expensive choice. Unfortunately, Ref. [23] shows that water vapor significantly degrades propagation at frequencies above 5 GHz. These considerations dictated the choice of 2.45GHz for most of the studies on SSP done to-date: If GEO is used, then the ground station size must be on the order of hundreds of kilometers in diameter (smaller receivers require larger transmitters in Space). Such a station can only be justified if very large amounts of power are transacted, which in turn makes all-weather operation essential. Lower orbits were rejected as being technically difficult due to the transient, dynamic power reception.

Because of these considerations, a 1GWe Space Solar power plant will cost orders of magnitude more than a 1GWe nuclear plant, and probably much more than any terrestrial renewable energy plant. We must go back to Table 1 and wonder whether the spurts of interest in SSP were indeed real, given that no fundamental breakout from the above constraints was identified, except with the recent JAXA proposal to use Nd-Cr fiber lasers that showed high conversion efficiency from the broadband solar spectrum to beamed infrared power.

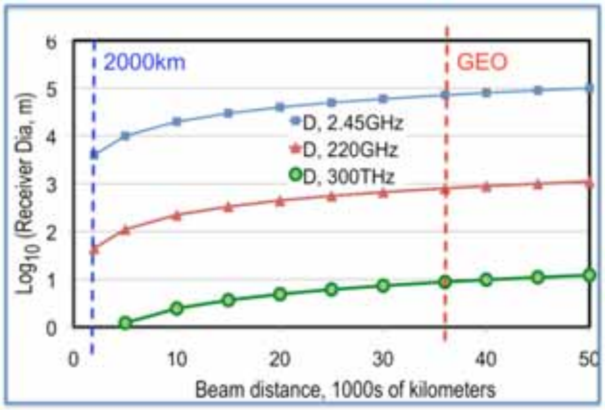

Figure 1: Receiving antenna size for 84% capture vs. beam distance

4. The Space Power Grid

The Space Power Grid architecture that we have been developing, argues for at least 3 radical yet logical changes.

1. 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 desperately 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 coming from their ability to win higher prices for their output, to use their peak generation without large on-site storage, and to avoid the need for 100% redundant auxiliary generation capacity (usually fossil-fuelled). 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 in 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. Figure 2 shows the concept. Table 2 shows conceptual design parameters. These are 4000kg class satellites placed into 2000km 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. The Phase 1 system is shown to be quite effective and viable, expanding to 100 satellites serving 250 ground stations by Year 17.

Phase 1 parameters are detailed in Ref [24]. This is just one embodiment of the system. Numerous permutations of launch rate, orbits and satellite/ power transaction size are possible, and we have not rigorously optimized the system.

Table 2: Phase 1 SPG relay satellite conceptual design parameters as of April 2011

Dry Mass, kg	2680
Total Loaded Mass, kg	3526
Volume, m^3	17.7
Packed length, m	4.6
Packed diameter, m	2.2

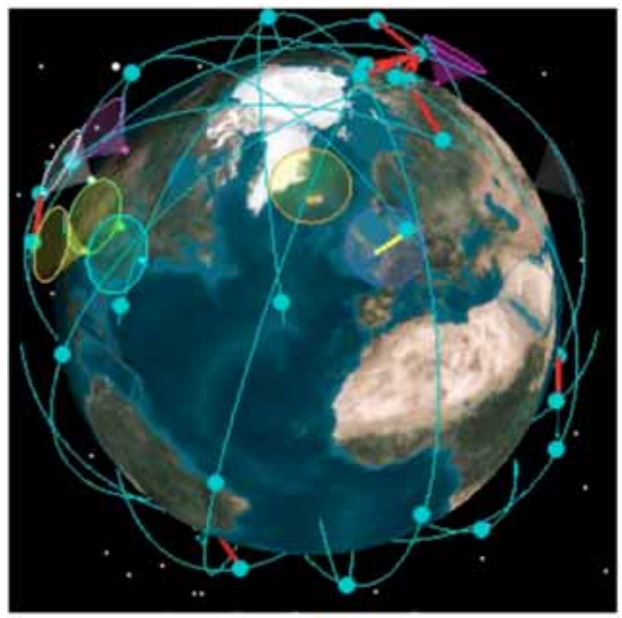

Figure 2: The Space Power Grid Phase One concept. Orbits heights are not to scale. Cones of visibility from surface power plants are sketched.

Phase 2 and Phase 3: 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. In the SPG architecture, these are by far the most costly items. Their collectors are sized to receive highly intensified sunlight, from ultra-light reflectors. At present we believe that it is best to place the 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 would be needed. Future developers may standardize a design converting much more than 1GWe, but at present we see no advantage to that. Figure 3 schematically illustrates the Mirasols (high-altitude reflectors), the Girasols (converter-relays in the grid orbits) and the small Phase 1 relays.

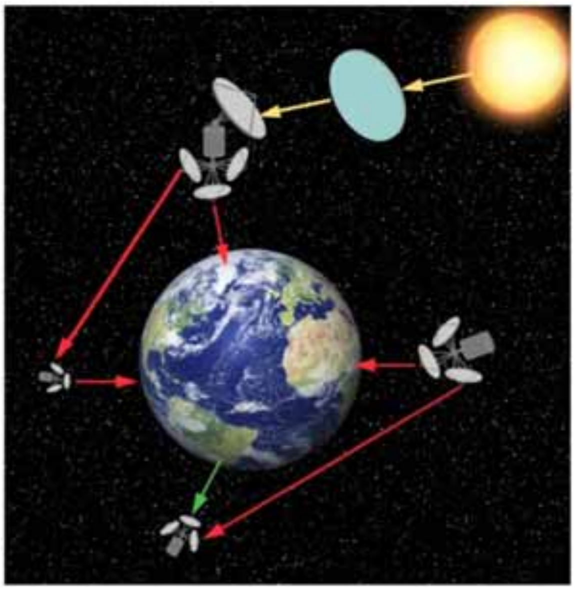

Figure 3: Cartoon representation of SPG Phases 2

5. ARCHITECTURE RESULTS

Present results from the SPG Architecture Model are given below. Model assumptions, and the basis of each, are detailed in Ref. [24] and are not repeated here. Ref. [24] is the latest in the evolution of our Space Power Grid Model. Refs. [24,25,26,27,28,29,30,31] have considered various aspects. These include the prospects for end-to-end efficiency, the impact of direct conversion technology and the crossover point in competing with the terrestrial power grid, relating frequency choice to economic feasibility, optimal power level, cost modeling refinements, active thermal control, the minimum number of satellites and ground stations needed for startup, and the selection of orbits. The issues in going to millimeter waves, the issue of obscuration due to weather and circumventing it, the public policy considerations in a global power exchange system, preliminary considerations for the retail power beaming end of the system, have also been considered.

Ngorongoro Viability Parameter k

As expected, none of the issues laid out above is "easy", but none is a show-stopper either, unlike the prospects for reducing launch cost to the levels assumed in most prior architectures, or achieving the ground receiver diameters assumed. For instance, see [32] for an excellent summary showing the assumptions in contemporary SSP models needed to achieve viable market prices for the delivered power. The state of the art in SSP is similar to that of the unique ecosystem in the Ngorongoro Crater [33]. The animals in this high-altitude crater are insulated from contact with the outside world by the high and steep crater rim, and hence limited to trying to dominate each other within that space. Surely the idea of trying to get out must have occurred to some, but all the options for doing so are very difficult. Some deep canyons are evident in the ridges, offering possible escape routes. However, there may be other unknown and insurmountable or impassable obstacles beyond the difficulties apparent from below. Likewise, there are several options that may be apparent to proponents of SSP, that will lead to the two order of magnitude improvement needed for economic viability. These may be summarized by an empirical thumb rule from numerous iterations of the SPG model. We thus define the Ngorongoro Viability Parameter **k**. Commercial viability requires that **k** be of order 1 (the minimum may be as low as 0.3 depending on other particulars).

$$k = 25000.P.s.\eta/c$$

The "." signifies multiplication and the "/" signifies division. The 25000 is a rough approximation of the many other parameters particular to each variation of the architecture, and of details such as required rate of return, cost of money, Isp of the in-space propulsion system, etc.

P is the price of delivered electric power in US$/KWhe.

s is the specific power of the system in orbit, KWhe/kg.

η is the efficiency of converted power transmission to the ground.

c is the launch cost in US$/kg to LEO, defined here as the orbital energy level from where the high-Isp space propulsion system takes over and moves the system to its desired orbit. Table 3 summarizes today's values, versus what is needed and reasonably achievable with R&D. There are as many different proposed solutions as there are streambeds coming into the Ngorongoro crater. Our choice is the SPG approach with millimeter wave beaming. As Figure 1 shows, it is essential to go well above 100GHz as the beaming frequency, and to reduce orbit height by an order of magnitude from GEO. The former drives us into the difficult regime of millimeter wave generation, reception and propagation, while the latter drives us into dynamic and transient beam pointing and reception. The technical arguments why these are fundamentally feasible are given in our prior work listed above. Much has changed in these technologies since the days when Peter Glaser and NASA/DOE laid out the GEO-based architecture. Certainly we are also keenly aware that there may be unknown and insurmountable obstacles along our chosen route, just as there are very visible ones in the GEO/5.8GHz architectures.

Table 3: Prior SSP parameter values, compared to what is needed for viability.

Parameter	Present	Needed
Power price, US$/ KWHe		
Beaming efficiency η	(0.1?)	0.5
Launch cost **c**, $/kg to LEO		
Specific Power **s**, KWe/Kg in space	< 0.3	>1
Ground receiver diameter, m	>100km	<1km

A few points can be mentioned without taking up much space in this paper, to address the primary superstitions that we have encountered in hearing the SPG system discussed among SSP experts.

1. Millimeter wave generation has been revolutionized by the automobile radar and Homeland Security market demands. While the frequency ranges used for short-range purposes is below 100GHz, components already use 220GHz generation. Mass production is possible, but specific power and efficiency values are not yet where we need them. We believe that there are several interesting alternatives here.

2. Rain above a threshold level kills millimeter wave power beaming. In fact it also kills low-GHz beaming as seen from the loss of satellite TV signals during American thunderstorms and Indian monsoons. However, there are wide swaths of the USA, for instance, where the probability of precipitation above this level is down to less than 5 or 10 hours a year; and this is true of most of the ideal locations for terrestrial renewable power plants (dry, high altitude, remote from population centers). With dynamic beaming, transient patches of rain can be avoided by selecting stations outside the rain area and using the terrestrial grid. This will however not work with GEO-based systems because the stations are so large and so few.

3. The atmospheric absorption data for millimeter waves comes from astronomical observation or radar imaging interests, where low signal level does not affect the air or its moisture content. When the interest is in continuous wattage (cw) beaming for several minutes, "burning through" or saturating specific energy levels of water vapor and oxygen of the atmosphere and creating a low-loss path is a much more interesting option. Winds are an advantage in this scenario because they allow the "burn-through" beam to be placed outside the main beam.

4. Phase-array antennae allow swift and accurate pointing of beams without physical movement of the hardware. The technology exists (whether published or not) since computation speeds reached desired levels in the 1980s for the aircraft-based Boost Phase Intercept problem of strategic missile defense. The problem of beaming to and from ground stations and satellites in well-defined orbits, is trivial compared to the BPI problem, but there may be substantial power requirements or losses in phase array pointing when applied to power beaming. For this reason the ground antenna for 220GHz may even use cam-driven mechanisms with servo motors for small corrections, since they are so much smaller than the versions imagined for the microwave/GEO options, and the motion is so predictable.

5. The SPG architecture is completely compatible with a move to lasers [34] instead of millimeter waves. Policy changes are needed to allow lasers, and atmospheric propagation of infrared lasers remains to be addressed.

6. The Phase 1 SPG satellites are relays. They do not convert from or to millimeter waves, and as such do not impose a large loss in the system.

7. Transient and intermittent beaming (irrelevant beyond the startup stage of SPG) are not fundamental obstacles to utility-scale electric power transmission in the 21st century, though they were considered killers in the electric grids of the 1960s. Wind power plants routinely face the reality [35] that wind power is proportional to the cube of wind speed, so that a doubling from 6 to 12 mph implies an 8-fold increase in power. The vast majority of wind power in most locations actually comes from transient windows of strong wind. Similarly, hybrid automobile technology assumes the ability to deal with sharp variations in power demand.

7. There are numerous choices for the SPG orbits. As pointed out in [27], the Molniya Orbits used by the USSR to achieve long visible times above high latitudes, may offer some options, but at the cost of a varying and perhaps large beaming distance. Ref. [20] considers a Molniya-type orbit for a space solar power satellite that provides long dwell time over certain Indian stations. We proposed to start SPG with a combination of near-equatorial and sun-synchronous orbits. Continuous beaming for 24 hours is not essential. The afternoon sun scenario shown in Figure 4 [28] uses just a few satellites following closely-spaced tracks in tandem, allowing solar plants to sell their peak output to others that are in the deepest part of their supply wells on the other side of the Earth. The number of satellites needed to achieve continuous beaming is much lower at the high latitudes (where GEO is too low on the horizon), so that SPG is an ideal system to reach those who have the fewest other alternatives to fossil-based power.

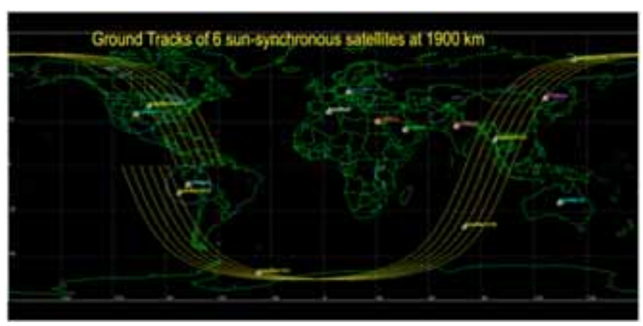

Figure 4: Afternoon Sun scenario where the first few satellites are sent in tandem sun-synchronous orbits.

Architecture comparisons

A "sanity check" for SPG was started by comparing with the JPL HALO architecture [32]. The summary comparison in Table 3 from [24] shows that for similar economic assumptions, SPG promises a major saving in the mass that must be delivered to high orbit. The mass estimate of SPG depends on using millimeter wave power beaming and achieving a high specific power of the conversion system (but with reasonable launch and development costs!) The way to achieve this has been proposed elsewhere. The basic breakthrough is that when the intensity level is very high and Gigawatt power level, gas turbine primary converters yield much better specific power than any pure photovoltaic system, as stated in Ref. [24]. In addition, there is a significant but not primary cost saving resulting from doing the mass-intensive power conversion in relatively low orbits compared to GEO. We note that when the move from LEO to the final orbit is done using high-Isp electric thrusters using spiral orbits, the difference between launch costs to GEO and 2000-km sun-synchronous orbits is not extreme.

Table 4: SPG Phase 3 mass results compared to HALO results in [32]. From [24].

Feature	SPG Phase 3 model	HALO[32]
Collectors	Ultralight solar sail configuration in high dynamic orbits	Heliostats in GEO
Converters	Heat engine /mm wave converters and transmitters in 2000km orbits	Intensified PV arrays/5.8GHz transmiters in GEO
Mass per GWe in high orbit	93 MT	10,870MT
Mass per GWe in low orbit	196 MT	0

As Ref. [24] showed (please see Ref. 24 for detailed parameter assumptions and rationale), the SPG Phase 1 system parameters are set so that the system breaks even in 15 to 17 years at a respectable Return on Investment, compatible with a public-private consortium, with only the development funding (<10 $B) coming from the taxpayer. This is the key to SSP. It establishes the market and makes space-based beaming "routine", in complete harmony and synergy with terrestrial renewable power generation and the national priorities of most of the United Nations. It sets the stage for the expansion to full SSP. The Girasol converters of Phase 2 are the massive investments, first launching in Year 17, and starting large scale SSP. The Phase 2 Mirasols follow immediately, boosting SSP to the GWe level. The expansion ramp from there to the TWe level of eventual SSP is a matter of national priorities: faster expansion comes at the cost of a large dip in the Net Present Value, while a slow expansion allows a quicker route to profitability, but continues dependence on fossils, longer. Our model shows that breakeven can occur by Year 50 at a modest (but not very low) cost of power, and at Consortium ROI levels.

6. The India-US Strategic Partnership Opportunity

Garretson [18,36] outlines the opportunity posed by the growing US-India strategic partnership. The idea of SSP as a centerpiece of collaboration in the Space area is gaining currency among Indian policy circles [19,37,38]. India has a pressing need for more electric power, and this need is much greater than what India's terrestrial power grid can handle. Veterans of the Indian nuclear power industry point out that reactor design size has been limited not by nuclear technology, but by grid capacity. Over 400 million people have minimal access to electric power, and live in rural India, which includes over 600,000 villages. At the same time, the explosive growth of mobile telephone access and usage in India (over 450 million mobile phone accounts in 2010) shows the pent-up demand for technology, and its ready acceptance, even at price levels that appear quite steep compared to the average income levels. In many regions both in India and in Africa, people own mobile telephones and routinely depend on them to conduct business and farming, but must literally walk large distances to go and charge these phones, or pay exorbitant costs for those first few watts and watt-hours. One can only begin to imagine the opportunities and wealth that will be opened up, if these people can access plentiful and reasonably priced electric power. The opportunity to re-think options for connectivity and electric power exchange is tremendous.

In [30] and [31] we laid out some preliminary considerations on how Indian villagers may be provided with access to electric power quickly. Our conclusion is that this is best done with a combination of terrestrial grid access points co-located with the extensive Indian Railways network as done for the mobile telephone network, and then hopping beyond that using retail power beaming. Where the terrestrial grid has too little capacity or reach, power may be effectively beamed from regional power plants, through high-altitude platforms (lighter-than-air airships in the stratosphere) and then down to receivers in each village. A fleet of several hundred such lighter-than-air platforms, basically inflated structures, floating above the weather) would make a dramatic impact on rural electrification, far faster than any expansion of the terrestrial grid alone.

The relevance to Space Solar Power comes from the fact that India is investing very heavily in clean solar power plants in the dry north and northwest, and in wind power plants in the south. Both of these are highly unsteady sources, the wind plants more so. A real-time power exchange would make a large difference to their viability, yet the domestic power grid is ancient, inefficient, unreliable and of very low capacity. At the same time, solar and wind power plants in the US are also struggling to survive in competition with the well-established US fossil and nuclear power industry and the very efficient, reliable US power grid. The US too needs many more solar and wind plants. The US and India are 9 to 12 hours apart in time zones, making for an ideal solar power exchange.

The India-US exchange is thus a unique opportunity to start the Space Power Grid approach to SSP with a systematic series of demonstrations. The following concept explorations illustrate the opportunity to minimize the number of satellites necessary to provide essentially continuous power exchange.

4-Plant Model

A demonstration model has been created using the Satellite Tool Kit (STK) using up to six satellites and up to four facilities. The satellites have a near equatorial orbit with an inclination of 15 degrees and an altitude of 5500 km above

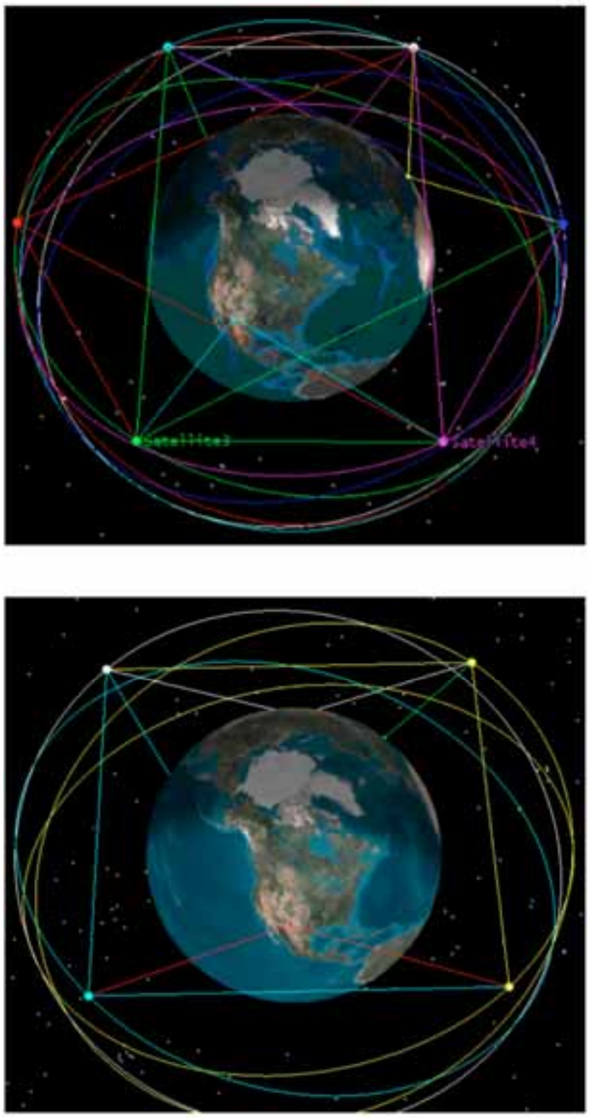

Figure 5: 6-satellite, 4facilty model (above) and 4-satellite, 4-plant model (below).

Earth, and have evenly spaced right ascension of the ascending nodes. Using the four facilities in our demonstration, United States (New Mexico, near Las Cruces), India (near Mumbai), Egypt (near Cairo), Australia (Western Australia) this model provides 24 hour continuous beaming to all plants. This orbit was chosen because the satellites never drop "too low" on the ground path to be seen by our chosen demonstration model facilities. The satellites are continuously in sight of each other, and at the same angle, meaning that no pointing is necessary for continuous space to space beaming. The low inclination angle that is relatively close to the latitude at the launch site (Cape Canaveral, FL) keeps plane change delta-v costs low. Figure 5 illustrates systems starting with six satellites (above) and only four satellites (below).

US-India 2-Plant, 6-Satellite Model

The demonstration model has been reduced to a two facility US-India model. Our model has essentially 24 hour continuous beaming, with a very small period of downtime that results because the two plants are not on exactly opposite sides of the Earth. Beaming in green represents New Mexico beaming to Mumbai; beaming in red represents Mumbai beaming to New Mexico. The model also has short periods of downtime that exist when the system is transferring from one 3-satellite chain to another.

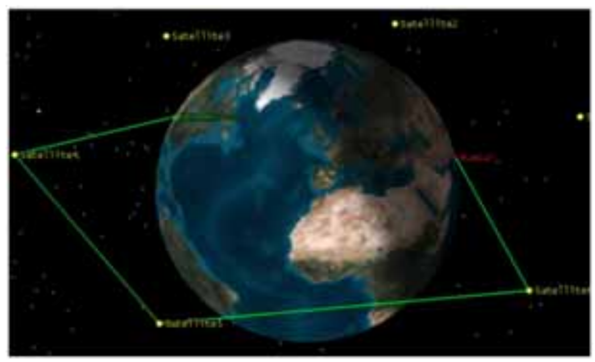

Figure 6: Six-satellite, two-plant model to start a direct US-India power exchange

Other variations of the US-India Model have been considered. Using a 3-satellite configuration at the current altitude (5500 km), there was very little time for beaming. Even extending the 3 satellites to 10000 km did not allow reducing the number to 3. We also looked at a 6-satellite configuration at 10000 km and it eliminated the gaps that the 5500 km version has when switching between satellites. In fact there is some overlap where one only needs to do beaming from one satellite to another satellite and back to Earth. Therefore, the ideal altitude for this startup demonstration with minimal number of satellites and ground stations, is somewhere between 5500 and 10000 km. Once the number of satellites increases, newer satellites will be placed as low as possible, which is probably at 2000km or even lower.

The 6-satellite, 2-facility model has continuous 100% beaming. The 4-satellite, 4-facility model has continuous 100% beaming for inclinations between 0-6 degree inclination. As a result, the inclination of our orbits in our model has been changed to equatorial. At 15-degree inclination, the New Mexico plant could receive beamed energy about 95% of the time.

These results are presented only for demonstration purposes, consistent with the basic research / initial concept exploration charter of our university research group. As the engineering of the demonstration model matures, surely other optimal configurations will become evident, with performance superior to what we present. For instance, the best locations for terrestrial plants in India may not be near humid Mumbai (Maharashtra) which receives heavy monsoon rains for several months, but perhaps in the Thar desert of Rajasthan, or the arid high plateaux of the Deccan in central India. The advantages of global collaboration cited by Dr. Abdul Kalam, former President of India, are brought home by the immediate advantage in number of satellites required to achieve continuous beaming, when more nations are included. Australia, Japan, New Zealand, the north African desert nations, the desert nations of the Middle East, the deserts of southwest Africa, parts of Russia, Chile, Argentina, Greenland, Iceland, island nations in the South Pacific, are all excellent candidates.

In this paper we have only looked at the number of satellites needed to maintain nearly continuous 24-hour power exchange. Satellite and ground station design, optimal levels of power beaming, costs and revenue are topics for future work.

Several technical breakthroughs must be demonstrated for the Space Power Grid approach to SSP to become reality. A systematic progression of demonstrations is laid out below:
1. Dynamic power beaming between a ground station and a satellite in a sun-synchronous orbit.
2. Terrestrial and earth-space-earth millimeter wave beaming at progressively higher frequencies, culminating in a 220GHz system.
3. Millimeter wave conversion efficiency improvements
4. Millimeter wave power beaming between satellites.
5. Waveguide type relay of millimeter wave power through a satellite to another satellite in space.
6. A 2-satellite, 2-ground station relay of millimeter wave power.

These will then lead naturally to the 6-satellite and 4-satellite systems describe above, growing from there to the full SPG.

7. Conclusions

1. Space Solar Power is an old dream that has provided a rationale for several initiatives. Renewed interest must be viewed with healthy skepticism, but careful analysis of opportunities.
2. The sheer scale of the SSP system needed to reach 4TWe of space-based power generation poses immense difficulties requiring new approaches.
3. To make SSP viable, improvements are needed in specific power, beaming efficiency, and launch cost.
4. Adoption of millimeter wave beaming and orbits at 2000 to 6000km in a Space Power Grid architecture, can provide order-of-magnitude improvement in viability.
5. Primary gas turbine power generation may provide the improvement in specific power required to close the viability gap, when used with SPG.
6. A US-India power exchange provides a unique opportunity to start the Space Power Grid towards full SSP.
7. With two more nations participating besides the US and India, it is possible to set up nearly continuous power exchange with 4 to 6 satellites in 5500 km orbits.
8. With only the US and India participating, a constellation of 6 satellites suffices to demonstrate a continuous power exchange.

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