Parameter Selection for a Space Power Grid

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This paper continues work on an evolutionary, revenue-generating approach to Space Solar Power. In previous work, a 3-stage, self-sustaining program was proposed, that enables growth to full Space Solar power in 20 to 30 years. The approach is to first use a constellation of spacecraft in sun-synchronous orbits as a microwave power grid connecting renewable energy plants situated around the world. This step generates revenue primarily from the large temporal and geographic variations in cost and supply of electric power. It enables location of new renewable power plants in remote locations, and minimizes reserve needs for baseload qualification. In a second phase, replacements for the first generation satellites would incorporate converters from solar power to microwave beams, followed by placement of large ultralight collectors in high orbits to beam sunlight directly to the converters. Recent developments have improved options in the near millimeter wave regime. In this paper, the Phase 1 architecture is altered to investigate the minimum power level at which the system will pay for itself in 30 years. Cost estimates are related to the published literature and shown to be conservative. Parameter choices are systematically related to the Net Present Value.

I. Introduction

The Space Power Grid concept illustrated in figure [1] is a way to integrate the need for renewable power plants with the grand dream of beaming vast amounts of solar electric power to Earth. In the first phase of the concept, Space is used only to exchange beamed power between locations on earth, thus enabling new renewable power plants to come up at suitable locations, and connect with customers anywhere on the planet. Such integration, we argue, enables an evolutionary, revenue-generating path to full-scale space solar power (SSP) that will also be compatible with public policy issues. The full system implementation is 30 years from project start, so that it is appropriate to project technological advancement beyond today’s levels. Accordingly, we expand our system parameter exploration space to include three assumptions:

1. Acceptable conversion efficiencies to and from beamed power will be available in the 200 to 250GHz regime.
2. Dynamic power transmission (i.e., to satellites in relatively low earth orbits) is feasible with high efficiency using phased-array antennae. This technology appears to be well-developed since the Strategic Defense Initiative of the 1980s, especially with the advancements in signal processing speed, precision and compact equipment enabled by the cell-phone industry.
3. Spacecraft thermal management concepts have advanced to where large heat loads can be efficiently converted to useful work, or to beamed power.

The purpose of this paper is to narrow down the parameter space where feasible solutions are likely, considering policy and economic issues in the system planning. We attempt to take the system exploration to determine the implications for the business case at zeroth order. The need for this is evident from a simple example: When beamed power is considered, the discussion usually gets deflected towards atmospheric absorption. However, a business case calculation would show that even a doubling of atmospheric absorption may be quite a small factor in the cost, if it enables gains in other aspects.

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A. Background

The large distance to geosynchronous earth orbit (GEO) has driven architectures for space solar power (SSP) towards very large stations with diameters on the order of kilometers,\textsuperscript{23} both in orbit and on the surface, connected by steady beamed microwave or laser transmission. This approach still leaves the problem of developing large infrastructure on Earth, feeding the power to the terrestrial electric grid. These design features do not offer any gradual approach to SSP. Several step-by-step approaches have been proposed,\textsuperscript{4,56} to reduce the cost to first power, but all except the Japanese Retail Beaming concept\textsuperscript{7} involve the ultimate use of satellites and beaming from GEO or beyond, or lunar power plants\textsuperscript{8} and earth-based receivers.

These developments have opened opportunities for a different way to achieve SSP. The rising prices of both fossil and nuclear fuels since 2003 have created a favorable public policy and economic environment for renewable energy resources for the first time since the 1970s. Global warming and local environmental concerns provide strong public support for power generation without carbon dioxide emissions, with the carbon credits and penalties providing strong economic incentives. Suitable locations for terrestrial solar and wind power plants are typically far from population and industrial centers, implying large transmission infrastructure costs. Large-amplitude fluctuations in power generation are basic features of solar plants and wind farms. These features impose high costs on renewable power, and make it difficult to earn baseload power plant status (CITE). The conventional solution is to set up auxiliary generators using fossil fuel to provide the backup capacity required to earn baseload status for renewable power plants.\textsuperscript{9} Obviously this doubles the installed cost per unit power capacity and negates much of the competitive advantage of going to renewable sources.

Demonstrations of beamed power started in the days of Nikola Tesla, and were advanced strongly by Brown\textsuperscript{10} in the 1960s. The idea of beaming microwave power to satellites in polar orbits has been investigated as early as 1988\textsuperscript{1}\ in the context of the Strategic Defense Initiative, as a way of maintaining the "housekeeping" power of satellites at a level of tens of kilowatts, with on-board storage/conversion using electrolysis and fuel cells. Phased array transmitters were proposed to direct thin beams to the satellites. Rectennae located on the satellites converted the received microwave beams to direct current and used chemical storage. In the SPG concept, the satellites act as waveguides, and do not perform conversion to DC, thus enabling much better efficiency in the power direction step. There is a large publication base on Space Solar Power, some of which is covered in Ref. 11.

The three phases of the Space Power Grid,\textsuperscript{12,11} are illustrated in figure\ref{fig:1}. In Phase 1 Space is used first as a power grid, connecting renewable plants at different locations on earth. New renewable plants will beam power to and receive beamed power from a constellation of 36 satellites in sun-synchronous and equatorial orbits at 800 to 1200km. These earth-space and space-space transmissions no doubt involve losses, but this has to be factored into the total system efficiency, and the business case for the power transaction. There are large differences in the price of power from time to time and place to place,\textsuperscript{3} which offer opportunities for profitable exchange of power, as realized by Bekey et al.\textsuperscript{6} Phase 2 commences when the SPG breaks even, and gradually replaces the constellation with satellites augmented with solar collectors and converters. In Phase 3 which proceeds as soon as Phase 2 puts enough converters in orbit, large, ultra-light solar collectors in medium-height orbits (a few thousand kilometers) will reflect broadband sunlight to the LEO converters. This is illustrated as a cartoon in figure\ref{fig:2}.

Several attractive features of the concept are listed below, based on the system described in Ref. 11.

1. Phase 1 is the basic Space Power Grid (SPG), consisting of 36 to 96 satellites in sun-synchronous and equatorial orbits at 800 to 1200km. These satellites will transact power between points on earth, taking advantage of time-zone, day-night and climate differences. Thus they will generate revenue and establish a firm customer base of new and existing power plants and retail receiver sites, quite independent of Space Solar Power. It is not expected that this phase must break even on revenue at the prices charged on the terrestrial grid in industrialized nations, since a fair amount of public funding may be expected in order to enable the renewable plants to come up, and to facilitate retail power transmission to places where there is no grid connection from large plants today.

2. Phase 2 commences after Phase 1 has established the infrastructure and generated substantial revenue the SPG breaks even. It replaces the aging constellation with satellites augmented with solar collectors and converters. This is the "grace period" for technological advancement, typically 15 years and beyond. Today we can assume that we will have at least the conversion efficiency and power per unit mass of today’s solar converters. If the issue is to convert to beamed power, it may not be necessary

Figure 2. Schematic representation of the Space Power Grid system in full deployment, showing earth-space-earth power transfers, augmented satellites with converters, and ultralight collectors beaming intense sunlight to converters in lower orbits.
to go through the intermediate DC step at all, so it is conceivable that the conversion may be directly
to beamed power using heat engines or other devices. This may be an extension of spacecraft thermal
management technology used in Phase 1.

3. In Phase 3, which can start concurrently with Phase 2, large, ultra-light solar collectors in medium-
height orbits or even in GEO, will beam broadband sunlight to the LEO converters. Thus the infra-
structure and construction / maintenance costs of the items in high orbits, are two orders of magnitude
below what is anticipated for GEO-based converters. There is no reason why visible-frequency sunlight
should not be beamed at very high intensity between two points in Space, since it will not be seen
from Earth. Since the power generated in this Phase simply adds to the existing SPG infrastucture
with an established customer base, the costs, risks and payback period of this scale-up phase are much
lower than with present concepts. It is possible that this phase can be done with the cash flow and
credibility established with the first phases.

4. The Space Power Grid can smoothen power plant output and turn them into "firm baseload sources"
that command higher prices. As a result, Energy producers can sell their large or fluctuating excess
capacity to distant customers willing to pay good prices. Distributors can receive "Green" power
matched to increasing local demand due to development. The SPG can reach areas at extreme lati-
tudes. Places lacking infrastructure for power generation or distribution, such as islands, deep forests,
mountainous areas and desert communities are good prospects to use the SPG. In disaster-hit areas,
mobile, air-delivered receiver stations can quickly restore power. Rapidly -deployed military forces can
quickly receive large amounts of electrical power anywhere on Earth. Beaming to in-space resources
is a relatively simple extension of the SPG. Competing power costs in this market are very high, and
hence this can be lucrative for the SPG.

Obvious risks are:

1. The system is dynamic, consisting of satellites in fairly low orbits, and thus requires constant control,
switching and large power transactions, like a modern-day terrestrial grid. These will benefit from
technologies taken from modern cell-phone adaptive antennae that track individual users using digital
signal processing. There are obvious similarities to beam weapon pointing problems as well.

2. Beam intensity at the satellites is large, posing material strength issues. It will pose a tough challenge
for wave guide efficiency, as well as thermal management.

B. Scope and Objectives

The rest of the paper is organized as follows. The choice of technical and economic parameters is first
described. The economic calculation basis and the results are discussed. Finally, the implications for
narrowing the parameter range are discussed.

II. System Parameters

A. Frequency

The frequency of the beamed power is a choice to be made early, and may be hard to change later. Early
system concepts used frequencies in the 2GHz range, to minimize atmospheric absorption by water molecules.
However, this leads to very large transmitter and receiver sizes. While the use of low orbits alleviates
the problem for conventional SPS concepts, the inter-spacecraft transmission required for the power exchange
function poses long distances, and demands unacceptably large antenna sizes, or the use of small antennae
with big leakage losses negates the advantages of low atmospheric absorption. In the 1980s, the published
efficiency in the millimeter wave regime for high-power applications was below 10 percent. Today there is
reason to believe that much higher values have been achieved; however, published data are hard to confirm.
Today, 95GHz beams are used in tactical weapons, with power levels adjustable down to the levels needed for
non-lethal crowd control from mobile field-deployed units. It turns out that the atmospheric absorption losses
at the 200-250 GHz range are low as well. Benford\textsuperscript{13} discusses applications to space propulsion and power
beaming. At 220GHz, atmospheric absorption losses are as low as 5 percent, when beaming to and from high-
altitude locations, and air breakdown is apparently not an issue even at the very high intensities discussed
there. Cloud cover greatly reduces transmission at these wavelengths. Using these frequencies results in much smaller antenna sizes. Compared to the 80-100GHz range, the 200-250GHz range offers advantages in propagation through atmospheric particulates, which made this range attractive for SDI considerations (one advantage mentioned was that these beams would remain effective through post-nuclear explosion debris clouds). The choice of frequency is thus a tradeoff between antenna size to capture a given percentage of the beam power, and the losses due to atmospheric absorption. This trade is skewed towards low frequencies, for a fixed-location system such as a GEO-to-equatorial surface link, where rain and cloud cover affect the reliability of the system. However, for a dynamic space power grid, with numerous options for getting power to a given location, the atmospheric loss problem is secondary. We use four frequencies to illustrate the effect: the 2.4GHz, 100 GHz, 220 GHz, and an Nd-YAG laser frequency. In the 220 GHz case and the laser case, antennae on the spacecraft can be sized to capture over 99 percent of incoming beam energy, while still requiring only modest antenna areas on the ground.

The largest uncertainty associated with choice of frequency is the conversion efficiency and associated cost in each part of the spectrum. One possibility is to shift to the infrared regime of the Nd-YAG fiber lasers, where conversion efficiencies from direct sunlight to beamed laser of an astonishing 38 percent, with theoretical limit of 40 percent, have been published. Given that this option exists, we proceed with the assumption that ground-based conversion (where mass per unit power is not a limiting concern) can be achieved at all the selected frequencies with wall-plug to beam efficiencies of 30 percent. If technologies arrive for converting power at one frequency to power at a vastly different frequency, with near-100 percent efficiency, then the atmospheric transmission should occur at a low frequency while the long-distance satellite-to-satellite transmissions should occur at high frequency (200GHz regime). Today we have no indication that this is viable.

B. Orbits

Orbit height influences the antenna sizes on the satellites, the launch costs, the fuel needed for orbit correction, and the interval of visibility above a given ground location within a given beaming cone. The last item is the limiting constraint. Sun-synchronous orbits at 800 km, chosen in our previous paper would necessitate distribution of the beaming antennae among several ground stations along the satellite tracks, with the number of beaming stations becoming roughly four times the number of generating power plants. Three cases are considered: Geosynchronous orbit as a reference case for comparison with previous SPS concepts, sun-synchronous orbits at 800 km, and polar orbits at 10,000 km. There are many additional options to be explored, including variations of the Molinya orbits used to increase loiter time at high latitudes. At system initiation, with only a few power plants participating, high-eccentricity orbits such as the Molinya may be appropriate to enable continuous beaming from a few ground locations for several hours a day. These may be combined with the other two circular polar orbits as the system expands.

C. Power handling per satellite

Given the cost of launching and operating satellites and that of setting up the ground infrastructure for beamed power exchange, the minimum level of power transactions that each satellite can handle, becomes a limiting factor. We explore three levels. A level of 250MW would enable exchange of most of the power from a modern 700MW power plant with 3 satellites in view. A level of 100 MW is intermediate, and a level of 10MW would bring spacecraft thermal management and antenna power-handling into a regime where experience is available.

D. Thermal Protection, Storage and Regeneration

The upper limit on power handling by each satellite is posed by thermal management issues. While the Phase 1 satellites are essentially passive antenna/waveguides with some beam steering, even a 99 percent efficiency implies a very large heat transfer rate, far above the experience level of modern satellites at power levels above 10MW. Closed-loop fluid heat exchangers that operate heat engines could convert part of the heat again to beamed power, transmitted to retail customers either in space or on the ground. This is certainly a difficult challenge. One approach is a closed-loop helium/xenon gas heat exchanger to remove heat from the highest-temperature portions of the system. The hot gases drive a turbopump. This system exchanges heat with an oil-salt mixture, which also provides stability during power fluctuations. The turbopump provides
on-board power, and pressurizes the Xenon propellant for the orbit correction system. The liquid system provides a way to store a small percentage of the energy for short durations. The independent generator provides a way to beam frequencies different from those used by the main grid. These aspects remain to be explored.

The mass of the TPS (minus any beamed electric generator) can be estimated crudely using thrust-to-weight ratios achieved by modern-day fighter jet engines, which produce roughly 100 to 125 MW. This shows that such a system can be confidently built under a mass of 2000kg. While substantial, this is not a show-stopper. One system can provide a constant power supply by storing the heat of fusion of LiF to store energy across hot and cold cycles and then transferring throughout the cycle by Xe gas.

E. Market Size

World primary energy consumption was 433 quadrillion BTU and rising at 2.2 percent annually. By 2030, the total market is projected at the equivalent of 45600GW installed capacity, at the usual 50 percent average operating level. Today over 50 percent of primary power generation is fossil, and the proportion that is converted to electricity is relatively small. This proportion could rise dramatically if clean, cheap, electricity became available. By 2025, global North American electricity consumption is projected to be 23072TWh, of which the US will account for 5025TWH. There are over 49000 electric power plants in the world, generating a total of 2812 GW, indicating an average capacity of around 57MW. Approximately 1100GW of this is in 4144 North American plants, at an average of 265MW. The average of the other 45000-odd plants is only 38 MW because developing countries invest in micro-power plants suitable to smaller community/rural electrification projects, while plants in the industrialized nations are concentrated into very large units. There are 774 “new generation” plants in the US, producing an average 310 MW of “green” energy. Newer nuclear plants (and wind farms) coming up around the world appear to be designed at a 700MW level on average. Retail Market Size is considered essentially unlimited, as the demand for energy is growing rapidly on earth, and the paying power of customers rises as energy becomes available for them to implement development in their areas.

F. Sizing Decisions Based on Market Considerations

Since wireless power beaming is currently only half as efficient as conventional wire transmission, most of the above plants will beam only part of their output. North American “Green” suppliers are likely to beam up large amounts of energy during peak generation periods. This energy may be distributed in small amounts to a large number of receiving stations. Given the 10:1 size ratio of plants between North America and the rest of the world, and given that each new plant may have 3 major receiving hubs, a ratio of 100 retail output beams to 3 large input collectors appears reasonable. Also, a 250MW capacity per satellite is adequate to soak up the entire output from all but the largest plants, or substantial output from three at a time. However, the power level per satellite may be limited by power-handling capability.

G. Internal Rate of Return

The Internal Rate of Return (IRR) selected for this enterprise is a low 8 percent. This is because it is anticipated to be funded by an International Space Infrastructure Consortium.\textsuperscript{15} The reasons why large space infrastructure is best implemented using such a consortium are discussed there. In our system, certain parts of the SPG will indeed be far more profitable than others.\textsuperscript{6} considered a segment with a 35 percent IRR); however, limiting participation to those markets will not permit expansion through the subsequent phases.

III. Methods

1. Cost figures have been referred to the NASA-USAF Cost Model (NAFCOM)\textsuperscript{16} as published on the internet with an interactive applet. This offers the Spacecraft Level Cost Model, where craft dry mass and number of items produced, are correlated with development and production costs, assuming an 85 percent learning improvement. This is a conservative estimating tool, since it is based on historical data, mostly with small-production run systems, in an age of fewer suppliers, and government customers.
2. Launch costs are related to the survey published by FUTRON\textsuperscript{17} for pre-2001 launchers. Here we do use the low end of the prices, on the argument that competition is bringing the price down, and the lowest prices set the target for their competitions to meet. Futron cites comments from western industry officials that launch prices have come down by 30 percent in 2000-2003, so this is a valid assumption. Launch costs to LEO and GTO differ by as much as a factor of 5, which is more than can be explained by physical criteria such as orbit energy (factor of 2.2) or launch mass ratio. The best explanation for the increased cost is the increased complexity and risk associated with achieving precise orbits at higher overall energy levels, usually involving first firing of another set of high-Isp engines. In practice, we use an exponential curve fit to the lower end of cited launch costs versus orbit height from 2000, and this gives an exponent of 2.3. This results in much lower costs than what we had used in.\textsuperscript{11} This is shown in

3. Given the total investment, the annual mission operating cost is estimated by going back to NAFCOM.

The process followed here is to decide on an acceptable Internal Rate of Return, and use the number of years to payback (zero NPV) as a metric. Sensitivity to different parameters is examined, in order to arrive at bounds for parameters within a given architecture. Given the high sensitivity to several key parameters, there are opportunities for widely different architectures.

\section*{IV. Narrowing The Parameter Range}

With the linkage completed from technical parameters to business case, the effects of various parameters could be explored. The current baseline is described below. The frequency is 220GHz. The earth-facing antenna on the Phase 1 satellites is arbitrarily fixed at 50 m diameter, the reasoning being that smaller diameters would imply very high beam intensities. The orbit height was varied, and the present baseline choice is a circular orbit 2000 km above the mean surface. Here the orbit period is just over 2 hours, and any given station under the satellite path can see it for over 9 minutes within a 45-degree conical sweep. Various choices of orbit inclination and precession are possible, but with at least 20 satellites, it appears possible for a given power station to achieve nearly continuous access to at least one satellite. At 2000 km height, the intersatellite beaming distance, assuming an exchange satellite located 45 degrees of earth azimuth away, is over 6000 km. This drives a satellite-satellite antenna (of which two are assumed on each satellite) with 130m diameter. This is a driver of the satellite mass. Smaller antennae may be used on later satellites in the constellation as the increasing number of satellites reduces the azimuth interval between satellites.

The system economics problem is framed as follows. A baseline design is found where there is breakeven in 30 to 31 years from project start. Phases 2 and 3 with augmented spacecraft that collect solar power and convert it onboard, will start long before this, but here we look at system parameters needed to achieve breakeven with just the Space Power Grid business model. Sensitivity to parameters is then explored, to see ranges of possible flexibility.

\subsection*{A. Sample Calculation}

In the following, the NPV calculation at Year 8 is used to illustrate and verify the numbers obtained.

1. Satellite Power Level: 60MW
2. Satellite mass: 4610 kg.
3. Launch cost to 2000 km high circular orbit: 19.8M dollars
4. Development cost for system: 330M dollars
5. Production cost for 1st 36 satellites: 1370M dollars
6. Ground facilities development cost: 1000M dollars
7. Per satellite annual mission operations and data analysis cost: 2.75M dollars
8. Ground station power level: 55MW
9. Cost of production of power: 4 cents per KWH
10. End-to-end efficiency of beaming power grid: 0.3
11. Sales price per KWH at delivery point: 30 cents. This means that only 30 percent of the power generated for beaming actually reaches the customer, who pays 30 cents per KWH for the power that s/he receives.
12. Gross margin per KWH: 5 cents, of which the SPG receives 90 percent, or 4.5 cents.

At the start of Year 8, the system has a cumulative NPV of -2.266B dollars. The cost of money including the IRR, at 6 percent, amounts to 136M dollars. Being renewable energy that would otherwise be underutilized, this is still a good deal for the generating plants, when added to the Carbon credits associated with the supply of energy. Six satellites are launched, costing 300M dollars to produce and launch, at 50M dollars each, bringing the total in orbit to 18. Six new power plants join the SPG system, costing 6.5M dollars each to set up transmission systems. This was paid in the previous year. This brings the total in year 8 to 17 stations. However, in Year 8, 33M dollars was paid for the 6 stations to come on line in Year 9. Mission Operations cost in Year 6 is 49.5M dollars, at 2.75M dollars per satellite. The power available to transact from the 12 plants totals 4100 GWH. The satellites could have handled a maximum of 4500 GWH, operating at 90 of their rated capacity. They provide 38 percent more coverage (time over the plants) at about 10 minutes per station, than is essential for full use of the power being beamed. This means that the cone of visibility can be reduced, thereby improving efficiency at each plant, without suffering drop-out in transmission. The SPG’s share of revenue minus cost of generation from this transacted power is 184M dollars. With this, the SPG suffers a net operating loss of 334M dollars, so that the cumulative NPV becomes -2.6B dollars. This is the 3rd year after system operation began. Year 18 is the first year when an operating profit (23M dollars) is seen, with the cumulative NPV reaching a bottom of -4.404B dollars at the end of the previous year. By Year 30 the NPV has turned positive.

B. Limiting values of satellite power handling

The first demonstration is that there is a severe lower limit on the amount of power that each spacecraft must handle. For this paper, we tried starting as low as 20MW per satellite, but were forced to settle on 60MW before a 30-year breakeven became feasible. The reason to go to lower power is to reduce the technical issues of beam intensity at the spacecraft, and the thermal management issues, since there is no available experience on useful handling of radiant heating of more several megawatts on spacecraft. However, our result is that this technical barrier must be faced. The other reason to stay at lower power is that the spacecraft mass is driven by the thermal management system mass as we get beyond 100MW. Technical advances are needed to obtain practical values of mass per unit power handled in the megawatt regime, and to reduce it below the 600kg per MW level that we assume for a fluid recirculation system, based on what can be done in aircraft jet engines.
C. System Growth

Figure 4 shows the growth of the Phase 1 SPG system in number of satellites in orbit, the number of power plants beaming power up, and therefore the amount of power being transacted each year. This shows the growth of the Phase 1 system tailored for best NPV in 30 years under the given constraints. The system is leveled off at 104 satellites and 103 power plants. As noted before, the intention is that by Year 23, as the first Phase 1 satellites come up for planned replacement, Phases 2 and 3 should commence, so the remaining portion of the NPV curve for Phase 1 is computed simply to show that the system would break even at 30 years with just Phase 1 at steady state. In practice, we expect that a drop in power price will occur as Phases 2 and 3 commence, and at any rate, competing systems will limit demand growth and force price declines. These interactions are not modeled here.

D. Public Funding to Reduce Price of Power

The price of delivered power is very high, and US-based urban consumers, connected to one of the most efficient high-voltage transmissions grids in the world to nuclear plants that have already amortized their investments, will recognize that 30 cents per KWH is two to times what they now pay. There are several answers to this. The first is that the initial markets for expensive beamed power will be to places where there is no electric power grid beyond the local area, and present prices are very high, as they depend on fossil power generation. A secondary market is to plants where the availability of power on demand smoothens fluctuations in plant output, thereby reducing the need for backup power generation. The marginal price for surge power and peak-demand power, is over 40 cents per KWH. So these initial prices are sustainable for a few years. Another obvious answer is that the baseline case uses no public funding, but expects to get long-term funding at 6 percent return on investment. This implies repayable public infrastructure / utility bonds with the risk underwritten by national or international government/ consortium entities. Figure 5 shows this. The scheme followed is to fund at a constant level that covers the up-front costs for the first five years, upto a maximum of 1.5 billion dollars, followed by a reduced level, flat across the next five years as the satellites and power stations increase along with the power transactions. Trading off initial public funding versus return on investment later, runs into the policy issue of how to justify up-front public grants, along with levels of return that imply profit-making ownership.

We point out that such a large international project without public funding at the start would be quite unprecedented. ROI large enough to attract private capital is not realistic for such a system because of the large risk, and the need for involvement of public financing to ensure serious intent on the part of governments to complete the project. The international cooperation implied in setting up the system makes international funding commitment indispensable for success. This issue is better left until the Phases 2 and 3 investment models are determined.

E. Summary of Present State of Knowledge

In our previous work, we assumed a low sale price for power, and determined the level of power that must be handled by each satellite to make the system profitable. We also assumed that Phase 2 would start as soon as the Phase 1 NPV curve passed its minimum. The design power level of satellites in that scenario was 250MW, which is a very high value, though it is well below the 1GW level at which breakdown problems are predicted, per the beam weapon literature. The high power level implied an extremely high thermal load on the satellites. We do not have a basis for estimating the mass of a closed-cycle thermal management system at the megawatt level. Given that there was no immediate solution for a high-efficiency generation
and switching technology in the 200 GHz regime, this merely meant that the development of the SPG system was quite far in the future. This was of course, still vastly better than the state of competing SSP concepts, which can make no viable business case.

Recent developments in the beamed power field, in both the industrial cutting machine field and in the military applications field, are believed to have made breakthroughs in the 200GHz regime. So an architecture based on that regime is now a short-term possibility. This means that we must investigate near-term system choices for the other major unsolved problems. The thermal load problem is thus circumvented by going to a power level much lower than before, and hence bringing the thermal management mass to a level where it does not drive the total mass of the satellite. Accordingly, we have investigated the lowest power level that makes sense, again by going through the economics of the full system. Further, we seek to prove the point about self-sustenance by taking Phase 1 to a full 30+ years, and showing that it does break even and turn profitable, even without starting Phases 2 and 3.

We see that the penalty for the lower power level per satellite (and plant) is that the price at which power must be sold is a high 30 cents per KWH. We then see what it takes to bring that cost down, and show that public funding for the first ten years, up to a total of 2.85 billion dollars, brings the power price down to just over 24 cents per KWH.

These numbers may still look high by the standards of the US terrestrial power grid, but we point out that the funding level is extremely low for a system of such fundamental importance to humanity, and that we are still showing a revenue-generating, self-sustaining path towards full Space Solar Power. The second and third phases are not discussed much in this paper, but will be left to future re-examination.

The business case for the renewable energy plants in a Space Power Grid is also a subject for separate examination. The issues there are interlinked with environmental and energy policy. As an example, the 0.002 cents per KWH of margin that is the share of the power plants, is matched by another 0.006 or so in carbon credits, if the power that reaches the customer is used to replace fossil-burning electric generation. The value of the power also rises, as fossil fuel costs rise. It is logical to project that there will be governmental or international subsidies to help the renewable power plants come up. For instance, the European Union is reported to be planning a massive solar plant in the Sahara, with a high-voltage DC grid going north and connecting to wind plants off the UK and Germany and distributing power throughout Europe. The SPG would provide a very versatile and powerful alternative to such a new terrestrial long-distance grid.

V. Conclusions

The Space Power Grid concept has been further explored, and linked firmly to cost-estimation models that are recognized to be conservative compared to what can be done at present and in future. The first phase, where Space is used only for power transmission and exchange, is analyzed with the constraint of 30-year break-even at public-financing level costs of money. The lower limit of power capacity per spacecraft is explored. The results show that:

1. A frequency of 220 GHz enables large advantages in spacecraft sizing, orbit selection and ground facility design, that far outweigh the small additional losses in atmospheric propagation.

2. The lower limit of power per spacecraft for breakeven operation is approximately 60 MW.

3. For the start-up phase, it is efficient to set power plant output levels just below the maximum power-handling capacity of the spacecraft.

4. With the 220 GHz choice, orbit height at roughly 2000 km above Earth enables system startup with only six satellites and six participating power plants, with initial launch in Year 6.

5. The system is expanded to a steady state size of 102 satellites and 101 power stations for the 30-year break-even criterion, with satellites replaced after 17 years of operation.

6. The Phase 1 system in isolation breaks even with no public up-front grants, and a 6 percent ROI, over 30 years.

7. Public funding of up to 2.85B dollars in the first ten years brings the delivered price of power down from 30 cents to 24.1 cents per kilowatt-hour during the breakeven period.
8. This implies that Phases 2 and 3 can be started at Year 23 with replacement satellites, on a profitable Phase 1 market and infrastructure.

References


