Systems Engineering for Space Solar Power Architectures

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Abstract. Concerns about the availability and use of conventional nonrenewable energy sources have led to an increasing interest in renewable energy. Because renewable energy sources tend to be dilute and intermittent, solar power satellites have been proposed as a means of supplying large amounts of power continuously. Space solar power (SSP) will not be competitive for commercial-scale baseload power without some combination of greatly reduced launch and non-recurring engineering costs as well as space resource utilization. However, SSP may be competitive in the near term for niche markets where the fully burdened cost of delivery of conventional fuel is much higher than that for commercial markets. A model under development provides a tool to assess masses and costs of solar power satellites at a variety of power levels, orbits, and power transmission frequencies.

Nomenclature

D_r = receiving array (rectenna) diameter
D_t = transmitter diameter
I_{av} = average power per unit area incident on a rectenna
I_0 = peak power per unit area incident on a rectenna
λ = wavelength of beam
P_t = power incident on the plane of a rectenna
x = distance between transmitter and receiver

0. Introduction

The future supply of clean, dependable, renewable and affordable energy to meet steadily growing worldwide demand in the face of the depletion and decline of conventional nonrenewable resources as well as growing concerns over the environmental impact of the continued use of existing fossil or nuclear prime sources represents one of the most fundamental and pressing issues that confront the global community at the beginning of the 21st century. It lies even at the heart of other major problems that plague especially developing countries around the world, such as the shortage of clean water. Cheap, reliable energy would allow the large scale desalination of sea water, which in turn would help to eliminate or alleviate the sources of several diseases endemic in various afflicted nations and also enable large scale agriculture in arid regions that are as yet infertile, thus addressing the incipient international food crisis and ensuring survival for millions of people. Similarly, electrical power is an essential prerequisite for the widespread use and implementation of modern communication systems and infrastructures that can be used to quickly and efficiently disseminate relevant and vital information to large audiences and populations, be it in the form of school, health and professional education, telemedicine, or even quick reaction disaster warnings.

Besides existing as well as novel terrestrial alternatives, the potential harnessing of the power of the sun by means of solar power satellites (SPS) that convert solar radiation into electrical energy and subsequently transmit it to the ground, notionally via microwaves, is a potential solution that was first suggested four decades ago by Dr. Peter Glaser[1] and later studied by NASA, U.S. Department of Energy[2], Boeing[3,4], and others. A variety of SPS architectures and configurations were designed (e.g., Figure 1). Most of the architectures have the same principle common elements such as solar arrays to collect the sun's energy and convert it to electricity and a large antenna array to convert the electricity to microwaves and transmit it to Earth. These would form the vast bulk of the SPS mass, though other elements (e.g. such as thrusters, avionics, and emplaced repair robots) would be required as well. Possible variants include using two microwave transmitter arrays instead of one (for symmetry), using solar thermal generators instead of photovoltaic arrays, and using lasers instead of microwaves for power transmission.

Based on technical advances in the areas of solar energy conversion and other relevant technologies, as well as the recent fluctuations in prices for traditional energy carriers such as crude oil, space solar power (SSP) has started to attract renewed interest. The advantages of placing the solar collectors in space include the unobstructed view of the Sun unaffected by the day/night cycle, weather, seasons, or the oblique angle of the sun at high latitudes, as well as avoidance of potential interference or sabotage, and the ability to beam power directly to remote users. The SPS is a renewable energy source, generates no emissions, and can be available for many years.

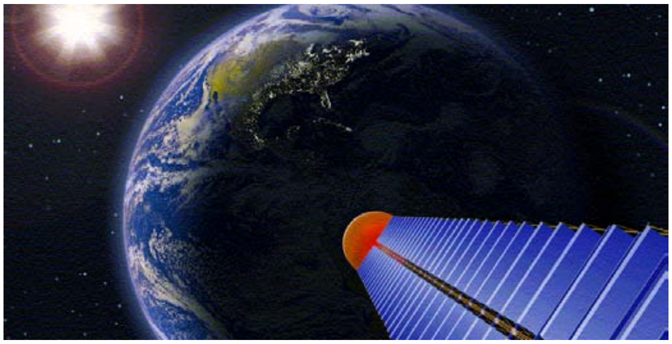

Figure 1. A Boeing concept for a Sun Tower solar power satellite would beam power from space to Earth via low-density microwaves.

Insofar as this approach uses existing space transportation systems, it is not yet economically competitive in major established markets; however, it is beginning to become attractive for niche applications, such as supplying remote locations without an existing power generation and distribution infrastructure or reducing the logistics footprint required for supporting temporary operations in disaster areas or military theaters. As economies of scale begin to set in, conventional energy sources continue to grow more expensive and burdensome, and synergies with other potential larger-scale space applications arise, solar power satellites might well become the preferred or even standard solution for satisfying the world's ever increasing energy needs. In addition, these solar power satellites will be aided by associated evolutionary or revolutionary technologies and systems, such as reusable launch vehicles aimed at the space tourism market, in space transportation, operation and utilization systems for asteroid deflection or mining or energy efficient orbital lasers for upper atmosphere ozone replenishment or planetary territorial defense.

Portions of the SIMILAR Systems Engineering process, as shown in Figure 2, were utilized in this analysis and assessment effort

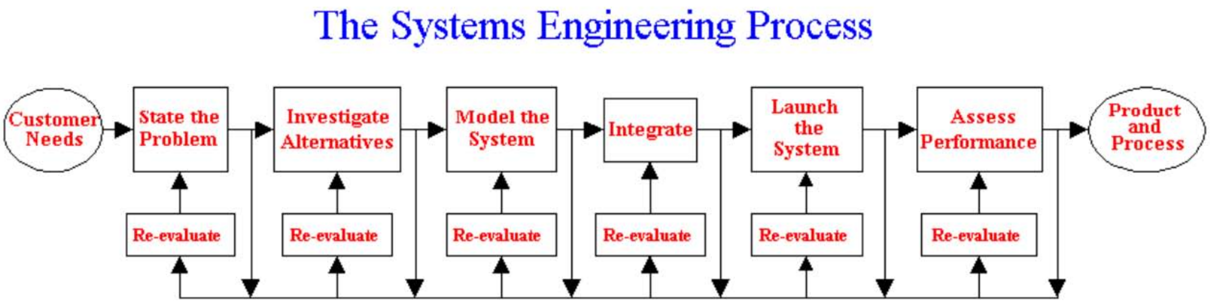

Figure 2. The SIMILAR Systems Engineering Process [4]

I. Systems Engineering Step 1. State the Problem

According to the US Government Accounting Office (GAO), the US Department of Defense (DOD) depends heavily on petroleum-based generators (primarily for heating/cooling, lighting, communications, and water desalinization) to sustain many of its forward-deployed locations around the world, and that these generators are the single largest battlefield fuel consumer. There are enormous logistics burdens and risk involved in transporting a million gallons of fuel every day to forward-deployed locations. A report by the Defense Science Board Task Force noted that 357 million gallons were consumed annually by Army generators. Fuel and water constitute approximately 70 percent of the tonnage required to position its forces for battle, and this high fuel consumption requirement on the battlefield places a significant logistics burden on military forces, exposing supply convoys to enemy attacks, severe weather, traffic accidents, and pilferage. “In 2006, a senior U.S. commander in Iraq submitted an urgent request to DOD for renewable energy systems in order to reduce supply line vulnerabilities”.[5] . In addition to physical risk and military mission degradation due to insufficient fuel supplies, cost is also a key factor, as the DOD has estimated that operating costs increase by approximately $1.3 billion for every $10 increase in the price of a barrel of oil. Since the cost of delivery and protection of fuel (“fully burdened cost of fuel”) can be much greater than the purchase cost, there is a niche market for alternative methods for delivering energy to military forward operating bases. This paper proposes space based solar power to fill that niche, and uses systems engineering techniques to determine the best solution.

II. Systems Engineering Step 2. Investigate Alternatives

The current study began with a definition of trade space of options that may meet current and future power needs through the implementation of space based solar power. In order to structure the systematic exploration of the various SPS system and architecture alternatives, first the associated top level trade space was mapped qualitatively. Figure 3 shows an excerpt of the resulting matrix of the major possible alternatives for a number of fundamental architecture characteristics as well as a color coding of an initial assessment of the feasibility and probability of the different choices, with blue denoting the state of the art baseline and the other colors across the spectrum marking less and less preferable or probable selections. These assessments represent the initial evaluation and were only meant as a point of departure for further work and refinement. They were in turn based on sets of associated evaluation criteria, a subset of which are shown with their respective color coding in Figure 4.. Here, red signifies showstoppers, which on their own can lead to a downselection of alternatives, while yellow, green and blue represent the next lower levels of criticality, with blue essentially being tiebreakers that would play a role only with all other factors being equal. Once again, this qualitative assessment reflects only a preliminary evaluation that may change with further study.

As indicated, a solar power satellite (aka SPS or Powersat) would represent an orbiting facility whose main function is to convert solar energy into electric power while in space and transmit this power (via microwave or laser) to Earth for various applications. The entire system, including satellites and ground stations, is often referred to as space solar power (SSP). While, as mentioned, solar power satellites cannot yet compete with power available from the U.S. commercial power grid, users in inaccessible locations (military, civil government, and commercial) may be willing to pay many times that rate, depending on the circumstances. As an example, one gallon of fuel may cost as much as $20 to deliver to soldiers in a war environment[6], with anecdotal suggestions of prices of perhaps $100 in some situations. Mixing economics and physics, one can equate 1 gallon of gasoline = 130 megajoules of energy = 36 kWh of energy = $100 for military users. Note that while this ideal consideration assumes 100% efficiency for converting thermal energy into electrical energy, conversion losses will make the actual requirement for fuel even higher.

At this rate, 40 remote military bases (using 5 MW each), will require 144,000 MWh in a month of use, consuming 4,000,000 gallons of fuel every month, costing as much as $400 million every month. These bases, using a total of 200 MW, could instead be supplied by just 20% of the power beamed from a single 1 GW power satellite. Graceful growth toward this market may be achievable by considering a constellation of smaller (5 to 10 MW) satellites. Consequently, there may be a business case for specialized applications like this in the short term, since the expected development, manufacture, and launch costs of a satellite could be less than the cumulative equivalent costs for petroleum-based solutions, especially since these satellites may last for decades.

Trade Categories	Trade Options					
Raw Materials Source	Earth	Moon	Near Earth Objects	Phobos/ Deimos		
Manufacturing and Integration Location (may be separate)	Low Earth Orbit (LEO)	Sun Synchronous Orbit (SSO)	Medium Earth Orbit (MEO)	High Earth Orbit (HEO)	Geostationary Earth Orbit (GEO)	Molniya Earth Orbit
Deployment Location	Low Earth Orbit (LEO)	Sun Synchronous Orbit (SSO)	Medium Earth Orbit (MEO)			
Space Transportation	Launch vehicles and spacecraft with chemical propulsion (expendable and reusable)	Spacecraft with solar electric propulsion (ion/plasma/ electromagnetic) (in space only)	Spacecraft with solar thermal propulsion (in space only)			
Energy Conversion	Photovoltaic	Solar dynamic/ thermodynamic/ magnetohydrodynamic	Thermionic/ thermoelectric	Solar pumped laser/maser	Signal processing solutions	Nanofabricated rectenna
Energy Transmission	Laser (visible/ Infrared)	Microwave/maser	Physical transfer of energy storage media	Cable (in GEO only)	Focused reflection	Relay satellites/ mirrors
Energy Storage	Supercapacitors	Superconducting magnetic	Reversible fuel cells	Batteries	Thermal storage/phase change material	High energy density matter
Electronic Components	Standard space qualified	Nanotechnology	Radiofrequency connections	Commercial off the shelf	Superconductors	Optical
Electronics Architecture	Distributed	Centralized				
Comand and Control Data Links	Radiofrequency	Laser (visible/Infrared)				

Key
- Potential Showstopper
- Highly Critical Decision Driver
- Critical Decision Driver
- Tiebreaker Only

Figure 3. Examples of assessment criteria for solar power satellite alternatives.

Trade Categories	Assessment Criteria					
Raw Materials Source	Accessibility (distance and required delta v)	Resource extractability (complexity of mining and refining operations)	Resource quality (concentration and purity)	Resource availability (mass)	Resource variety (type)	Space environment
Manufacturing and Integration Location (may be separate)	Accessibility (distance and required delta v)	Space environment	Available in space infrastructure			
Deployment Location	Insolation	Accessibility (distance and required delta v)	Visibility from receiving location	Distance to Earth	Potential interference with other space systems	Potential synergy/ collocation with other space systems
Space Transportation	Launch reliability	Payload mass per launch to destination	Achievable launch rate	Transfer time to destination	Total launch cost per payload mass	Available payload volume
Energy Conversion	Conversion efficiency	Power conversion capacity per mass	Reliability			
Energy Transmission	Transmission efficiency	Power transmission capacity per mass	Transmission accuracy and interference risk			
Energy Storage	Storage efficiency	Energy storage capacity per mass	Energy storage and release rate per mass			
Electronic Components	Memory sizes	Data rates	Reliability	Required power	Total life cycle cost per mass	Operational life
Electronics Architecture	Redundancy	Resiliency	Reliability	Required power	Total life cycle cost per mass	Operational life
Comand and Control Data Links	Bandwidth	Transmission range	Reliability	Required power	Transmission security and risk of interference	Installed mass

Key
- Baseline (Most Preferred) Option
- Highly Preferred Option
- Less Preferred Option
- Least Likely Option

Figure 4. Examples of alternatives for solar power satellites.

III. Systems Engineering Step 3. Model the Systems

In order to gain a comprehensive overview over the current state of the art in the major technological areas associated with corresponding designs, understand the implications and constraints of different concepts and identify promising approaches, solutions, and growth paths, Boeing has undertaken an internal study effort to review and analyze the existing body of work on this topic and subsequently develop scenarios and synthesize architectures that offer potential pathways for the implementation of large scale solar power plants in conjunction with other space exploration and utilization efforts, in particular, lunar colonization and in situ resource utilization. The main objectives are to identify the long range needs and plans for international space missions and systems related to transmitting energy from space-based solar power satellites to Earth as well as to investigate potential business cases for human space exploration and utilization with respect to SSP. The approach is based on the initial identification and definition of potential alternatives through literature research and a subsequent analysis and synthesis process using various modeling approaches to harmonize and validate the data and derive near-optimum solutions for various applications.

The study is aimed at addressing the stepwise process needed to achieve a mature SSP satellite constellation and assessing the costs and returns on investment (ROI) involved with the development of such systems. In addition, the technologies and architectures needed to realize such a system can be analyzed, resulting in technical roadmaps.

The Space Solar Power study modeling architecture has three major elements, which interrelate with our Lunar Colonization study as shown in Figure 5.

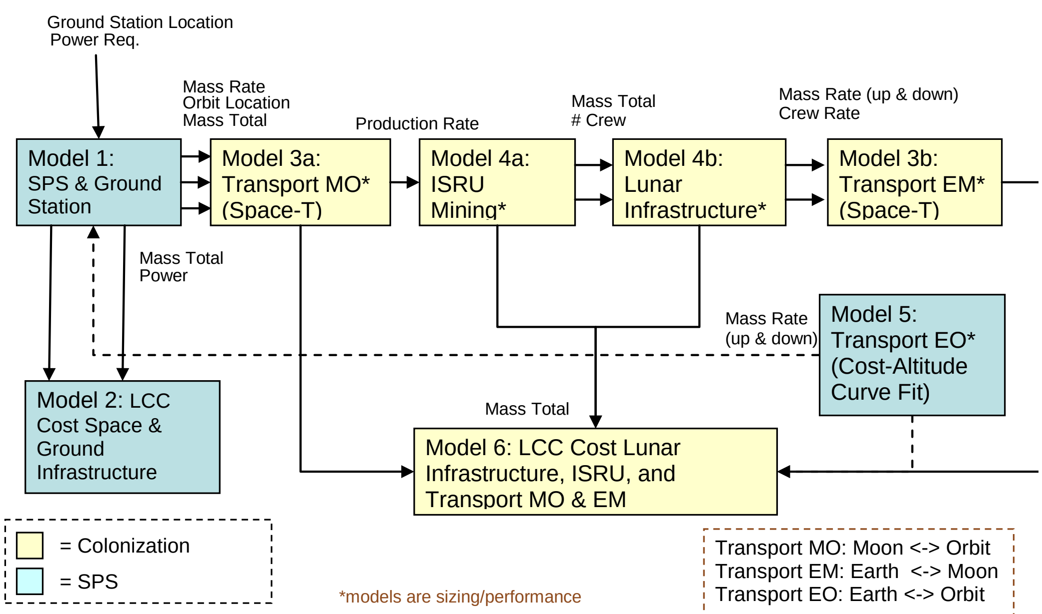

Figure 5. The Space Solar Power model interfaces with the Lunar Colonization modelto yield Solar Power Satellite masses and costs.

A principle driver for the size of an SPS is the divergence of the power beam through diffraction as it is transmitted over the distance between orbit and Earth. The diffractive effect will produce a main beam lobe that will peak in the center and trail off to a null. The main lobe will be surrounded by sidelobes. This divergence is proportional to the transmission distance and wavelength and inversely proportional to the transmitting antenna array diameter, or the diameter of the optics in the case of laser wireless power transmission (WPT). These parameters are related as follows:

$$\frac{D_t\, D_r}{\lambda\, x} = 2.44 \qquad (1)$$

Equation (1) applies to a uniformly illuminated transmitting aperture beaming power to a receiving array located in the far field. If the transmitter and receiver antennas are sized according to Eq. (1), then the entire main lobe, containing 84% of the power in the beam, will be captured. Eq. (1) is applicable no matter what the actual amount of power is in the beam. By tapering the energy across the transmitting array, the sidelobes can be reduced; this will also cause the main lobe to widen, thereby altering the constant in Eq. (1). For the level of detail in the current study, it was sufficient to consider an untapered transmitted beam.

A solar power satellite must be sized to give an appropriate power intensity per unit area at the receiver site. The power intensity is given by Eq. (2). If it is too low, insufficient power will be received to make the system economical. Rectenna efficiency may suffer and the cost of the land that it covers may render a low-density system unprofitable. If power density is too high, environmental and safety issues may arise.

$$I_0 = \frac{\pi P_t}{4} \left\{ \frac{D_t}{\lambda x} \right\}^2 \qquad (2)$$

These equations form the basis for our SPS size model. Algorithms were devised and tested using Excel and Mathematica, then integrated in Design Sheet. The Design Sheet tool allows independent and dependent variables to be switched. For the present study, I_0 was set to 23 mW/cm^2. Thus, for niche markets with a given power requirement and limited land for building a rectenna, D_r and P_t can be fixed and various combinations of wavelength (λ) and distance (x) can be examined to see what size transmitting antenna (D_t) is required to focus the power to the desired intensity. The current study is meant to give approximate results, so it was deemed sufficient to use orbital altitude for x. Future studies may use orbital slant range, either instantaneous, or averaged over the ground station access period. An example of the effect of requirements on transmitting antenna sizing is that of military bases. The National Security Space Office (NSSO) Space Based Solar Power (SBSP) Study Group has recommended that a study be performed that will lead to an "orbital demonstration of the key underlying technologies and systems needed for an initial 5-50 MWe continuous SBSP system." [7]

The size of the SPS solar arrays is driven by the client power requirements. For a limit of 23 mW/cm^2 peak (5.26 mW/cm^2 or 52.6 W/m^2 average), if a total of 41 MW is incident on the rectenna, then the actual amount into the grid may be about 29 MW based on a typical rectenna efficiency of 70%. A rectenna sized to capture 10 MW will yield 7 MW into the grid for 70% efficiency. The actual rectenna efficiency will be frequency-dependent[5]. For frequencies below 10 GHz, where the atmosphere is most transparent, transmitting antennas must be extremely large, except at low orbits. For higher frequencies, higher orbits are feasible due to the scaling of transmitting antenna size with wavelength. A geostationary Earth orbit (GEO) orbit using 245 GHz WPT may require a transmitting antenna whose size is within the realm of feasibility today.

However, higher frequencies, even those that are regarded to be in atmospheric windows, will still have some attenuation in clear air, and will fare poorly in rain and clouds.

Our analysis also included an assessment of cost, which is strongly driven by mass, both directly and through the effect of mass on launch costs. Thus, for high orbits (which maximize dwell time) and lower frequencies (which maximize atmospheric transmittivity), the massive transmitting antenna will dominate costs, unless the solar array is very large. The result is that small SPSs using microwave power transmission may not be feasible, at least in geostationary orbit. This has led to an increasing interest in laser WPT. The energy from the laser would be converted to electricity at the Earth's surface by a solar array whose bandgap closely matches the laser wavelength. This has the potential of bringing system size and cost to first power down. However, the lower efficiency of lasers, compared to microwave devices, the perception of risks of lasers, and the attenuation of laser light by clouds has, so far, kept microwaves under consideration, though by no means exclusively so.

A literature search was performed and historic mass estimates for major SPS subsystem components such as microwave transmitters and solar arrays were obtained. These were used to calibrate our model. Our cost model is shown in Figure 6. Laser WPT may be investigated in future studies. The microwave system mass/power relationships were entered into our size model so that once power, wavelength, and transmitter diameter were entered as client requirements or calculated from Eqs. (1) and (2), masses can be determined. Note that from Eq. (2), if the power level (and hence solar array mass) decreases, then the transmitter diameter (and hence the transmitter mass) must increase to maintain the same peak beam intensity. There will therefore come a point at which further reductions in power will actually cause the mass of the SPS to increase. The same will be true of the SPS cost. The lowest cost power level may not be the same as the lowest mass power level, with the difference depending on the relative costs of the solar arrays and transmitting antenna elements.

A notional plot of mass as a function of power level for GEO solar power satellites is shown in Figure 7. The curves turn upward toward the origin because for low levels of power, the mass of the transmitting antenna dominates. This is particularly visible for the 2.45 GHz frequency. Hence, SPSs supplying less than about 1500 MW do not make sense at that frequency. The lowest feasible power level point is less obvious with higher frequencies, but does go down as frequency goes up. It is seen that a 2.45 GHz SPS is heavier than those for higher frequencies for power levels less than about 5 GW, with the other frequencies having little difference from one another. Because frequencies higher than about 10 GHz are subject to rain attenuation, the 5.8 GHz frequency was chosen for cost analysis. Assuming modest improvements in today's launch vehicle technology, the result is a cost of $240 per installed watt (including production and launch, but not non-recurring engineering), or about two orders of magnitude too high to compete with terrestrial energy sources.

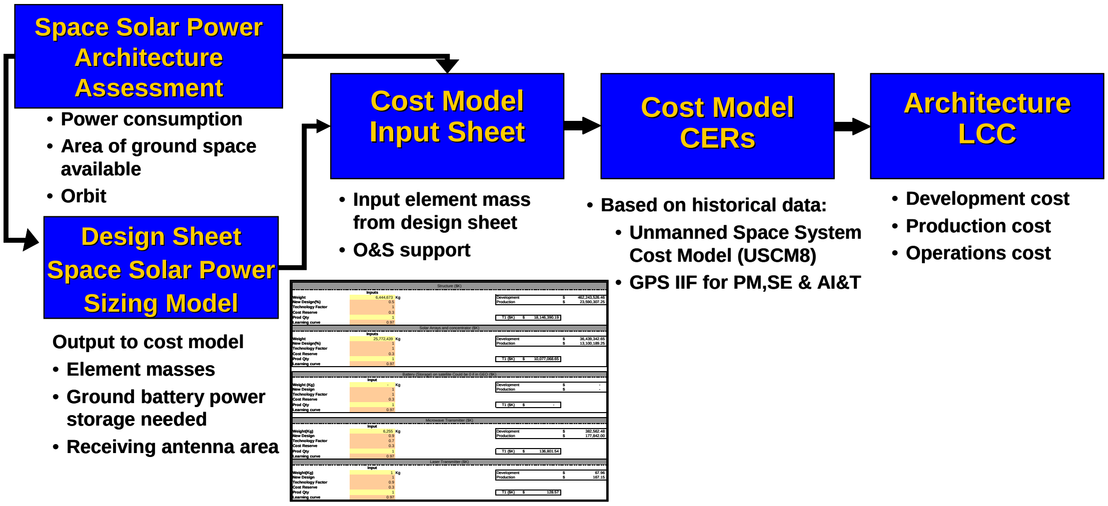

Figure 6. Cost model process flow overview. Design Sheet mass outputs, architecture structure, and model inputs are used to determine element costs.

The model was also used to size small solar power satellites that would supply power to forward military bases. An altitude of 350 km was chosen to minimize transmitting antenna sizes and provide possible traceability to power beaming demonstrations that have been suggested for the International Space Station or the Space Shuttle, which orbit at approximately that altitude. From Figure 8, it is seen that the notional mass of a 5 MW SPS beaming power at 35 GHz is about 25 metric tonnes, which is the approximate upper limit of launch vehicles available today. The model gives an installed cost per unit power of $145/watt for a 10 MW satellite. Satellites for somewhat larger military bases can be assembled in just a few launches. The costs assume continuous use of the satellite throughout its orbit. To achieve these costs will require that many satellites be deployed, with orbit tracks that take them over many ground receiving sites. Access to a typical ground station was assessed and is approximately one hour per day line-of-sight, horizon-to-horizon. However, beaming from a low Earth orbit satellite may not be practical during the entire time the satellite moves from horizon to horizon. Terrain and buildings may block the beam for very low elevation angles. If the elevation angle is constrained to a 10° minimum (similar to what may be imposed on analysis for communications satellites), then the access time is about 6 minutes, with two such accesses to a given ground station per day. If a constraint of 30° minimum elevation angle is imposed, then there will be two satellite accesses per day to a given ground station, about 2 and a half minutes each. It may be necessary to impose the latter constraint, because at 30°, the cosine loss alone will cause the beam to elongate to twice its minimum length, and thus half its intensity, with an additional loss due to the increased slant range, as well as increased atmospheric losses for frequencies above 10 GHz. Thus, beaming from the ISS or Space Shuttle may allow for sufficient access time for a proof of concept or demonstration; i.e., characterizing the beam or lighting up one bulb or light-emitting diode. However, for practical economical power beaming, a constellation of many satellites will be required with frequent beam handoffs. It will likely be more economical to launch fewer, perhaps larger satellites, to a higher orbit of perhaps a few thousand km. The specifics of the orbital constellation geometry will depend, to a large extent, on the locations of the bases that are to be served.

Although solar power satellites in lower orbits may serve specialized niche markets, the geostationary orbital belt will be the likely location for large-scale commercial SPSs due to their fixed location and orientation with respect to the rectennas on the ground and the markets they will serve. In addition, the beams from GEO satellites will not have to be slewed, which will eliminate scan losses and minimize the impact of moving beams on air traffic management.

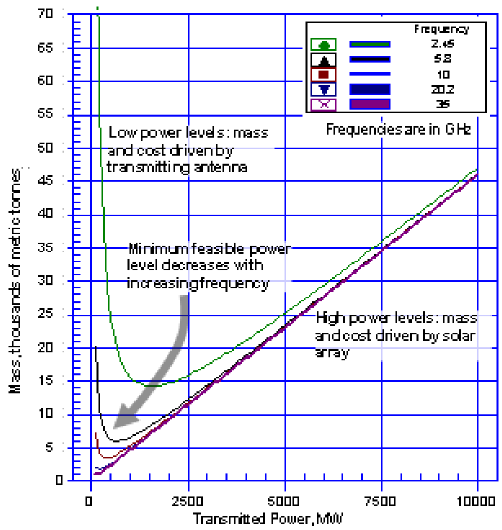

Figure 7. Notional GEO SPS mass for several power beaming frequencies.

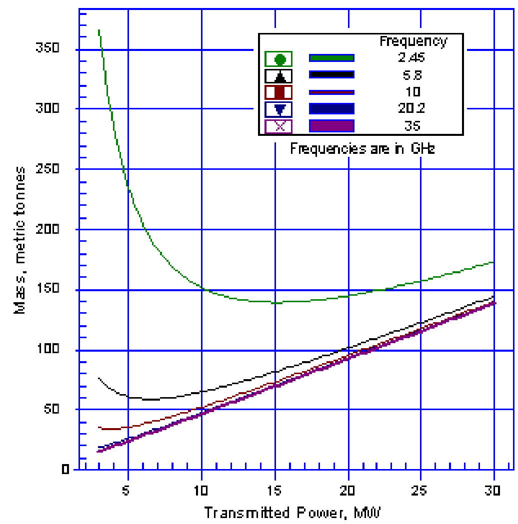

Figure 8. Notional masses of small SPS's in a 350 km low Earth orbit. Such an SPS can supply power to forward military bases.

As seen in Figure 9, satellites in GEO can serve much (though not all) of the world's population. If 30° is set as an approximate lower limit on useful elevation angle for the reasons stated above, then locations between the red horizontal lines in Figure 9 can be served by GEO SPSs. This includes all of the contiguous 48 U.S. states, some of the more heavily populated regions of Canada, southern Europe, China, India, and nearly all of the populated Southern Hemisphere land masses. This includes all of the developing nations where most of the energy growth in the coming decades is expected to take place. In some locations, such as Canada, northern Europe, and Siberia, it may be acceptable to receive beamed power at an elevation angle less than 30°.

One of the challenges facing the deployment of geostationary SPSs is the allocation of orbital slots in the GEO belt. Within the United States, the Federal Communications Commission (FCC) International Bureau, specifically the Satellite Division[8], authorizes non-government satellite systems. Fixed Satellite Service (FSS) satellites in geostationary orbit, must obey the FCC's orbital spacing policy created in 1983. This policy requires FSS satellites have a minimum separation of 2 degrees. This implies that the GEO belt has a total capacity of 180 satellites, though the current number is approximately 270, not counting government satellites. Preceding this policy, geostationary FSS satellites were positioned 3 or 4 degrees apart. The two degree separation policy was instituted to maximize the number of satellites in geostationary orbit, while preventing harmful interference to adjacent satellites. "Stacking" several satellites in a single slot, often by an individual owner, increases the capacity of the GEO belt by varying the eccentricity and inclination slightly so that the sub-satellite points of satellites in a slot make small circles or figure-8's around a point on the equator. Due to the limited number of GEO slots, the FCC ruled that all satellites, licensed in U.S. and launched after March 18, 2002, must be transferred into "graveyard orbits," 200-300 km above GEO after they have been decommissioned. Future studies will have to address the spacing of SPSs in GEO, as well as sharing the GEO belt between FSS satellites and SPSs as well as repair, salvage, and disposal operations of SPSs. The issues for SPSs are somewhat different in that electromagnetic interference with one another's ground stations is not an issue as it is with satellites that transmit information. However, maintaining acceptable levels of microwave radiation on the ground (as beam sidelobes overlap), in the atmosphere, and in space (i.e., at the locations of GEO and non-GEO communications and navigation satellites) must be considered, due to the more intense nature of the power beams. Avoidance of orbital collisions between SPSs that may be several thousand meters across must also be considered, as the debris field of a single SPS, or even a portion of one, could take out the entire geostationary communications system. One possibility for the relatively early deployment of at least some geostationary power collection and transmission capability is to consider empty slots in the GEO belt. Figure 9 shows the elevation angle contours of a GEO SPS at 150° west longitude, which is at the eastern edge of the empty Pacific region of the GEO belt. SPSs further west over the Pacific Ocean can beam power to Australia and eastern Asia. In the long term, SPSs and communications satellites may share common platforms.

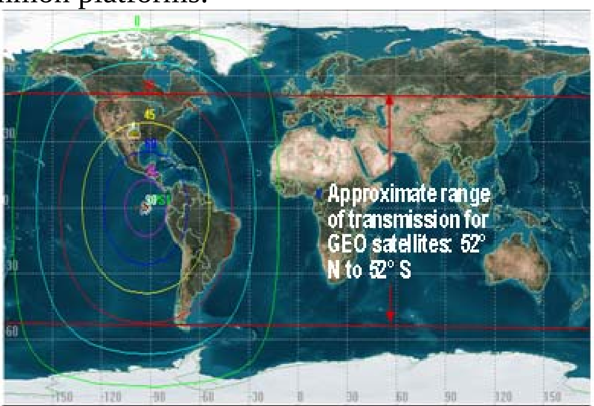

Figure 9. Elevation angle contours for a geostationary SPS at 90° west longitude. Even with a minimum elevation angle of 30°, most of the world's population can be served by solar power satellites in the geostationary orbital belt.

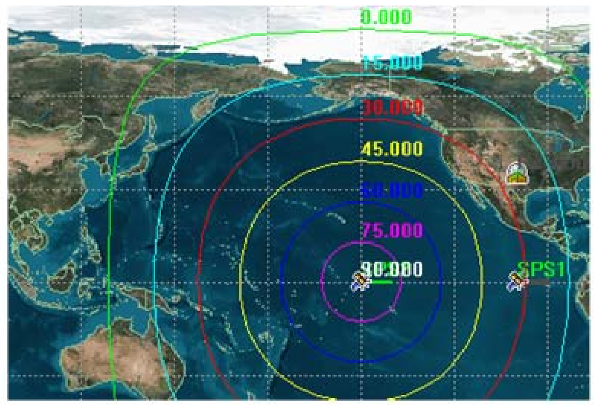

Figure 10. Elevation angle contours for a geostationary SPS at 150° west longitude. An SPS at this location can beam power to the west coast of the United States and Mexico, while maintaining a reasonable separation from presently operational geostationary communications satellites.

IV. Conclusion

Conventional (non-renewable) energy sources depend on a more-or-less continuous supply of combustible or fissionable fuel that is ultimately limited in availability and must be extracted – often from politically unstable parts of the world – and transported to points of use, sometimes at great expense and risk. Furthermore, the possible environmental effects of the waste products of conventional energy production have been the subject of increasing concern. This has led to an increased interest in renewable energy. However, renewable energy has its own challenges, particularly intermittency and a low area power density. Space solar power, by contrast, is continuous if delivered from geostationary orbit, and is predictable even if delivered from other orbits. SSP has challenges of its own, including high launch costs and high costs of non-recurring engineering. Other challenges include space industrialization and operations, and the need to construct extremely large structures in space. Microwave beam divergence drives up system size, making graceful growth difficult. Laser beams diverge much less, allowing for more flexibility in system size, but have other challenges such as low efficiency and weather outages. Achieving a graceful growth path toward large-scale SSP may involve finding an anchor customer, such as the U.S. Department of Defense, which may wish to reduce the logistics chain to forward military bases by displacing diesel fuel used to run generators with renewable energy. Demo-scale SPSs in low Earth orbit can be brought on line and beam power to the bases, thereby displacing a portion of the diesel fuel. By use of beam handoffs, the duty cycle of both the space and ground segments can increase as the number of satellites increases. Eventually, the power beaming concept of operations can be simplified by use of geostationary SPSs. At first, they can be deployed in unused GEO orbital slots over the Pacific Ocean. As U.S. and international law are applied to the needs of SSP, methods of sharing the GEO belt between many solar power and communications satellites can be worked out.

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