Power Generation From Solar System And Methods For Efficient Power Transmission From Space

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ABSTRACT

Solar power generation is being touted as a solution to our ever-increasing energy consumption and dependence on fossil fuels. Satellites in Earth's orbit can capture solar energy through photovoltaic cells and transmit that power to ground based stations. Solar cells in orbit are not hindered by weather, clouds, or night. The energy generated by this process is clean and pollution-free. Although the concept of space-based solar power was initially proposed nearly 40years ago, the level of technology in photovoltaic, power transmission, materials, and efficient satellite design has finally reached a level of maturity that makes solar power from space a feasible prospect. Furthermore, new strategies in methods for solar energy acquisition and transmission can lead to simplifications in design, reductions in cost and reduced risk. This paper proposes using a distributed array of small satellites to collect power from the Sun, as compared to the more traditional SSP design that consists of one monolithic satellite. This concept mitigates some of SSP's most troublesome historic constraints, such as the requirement for heavy lift launch vehicles and the need for significant assembly in space. Instead, a larger number of smaller satellites designed to collect solar energy are launched independently. A high frequency beam will be used to aggregate collected power into a series of transmission antennas, which beam the energy to Earth's surface at a lower frequency. The inter-satellite rectenna devices can also be smaller and lighter in weight.

Our paper suggests how SSP satellites can be designed small enough to fit within ESPA standards and therefore use rideshares to achieve orbit. Alternatively, larger versions could be launched on Falcon 9s or on Falcon 1s with booster stages. The only satellites that are constrained to a significant mass are the beam-down satellites, which still require significant transmission arrays to sufficiently focus the beams targeting corresponding ground stations. With robust design and inherent redundancy built-in, power generation and transmission will not be interrupted in the event of mishaps like space debris collision. Furthermore, the "plug and play" nature of this system significantly reduces the cost, complexity, and risk of upgrading the system. The distributed nature of small sat clusters maximizes the use of economies of scale.

Keywords - photovoltaic, SSP Cluster, rectenna, beaming satellite, Collectors and Beamers.

I. INTRODUCTION

Space-based solar power (SSP) generation is being touted as a solution to our ever-increasing energy consumption and dependence on fossil fuels. Satellites in Earth's orbit can capture solar energy through photovoltaic cells and transmit that power to ground based stations. Solar cells in orbit are not hindered by weather, clouds, or night. The energy generated by this process is clean and pollution-free. Although the concept of space-based solar power was initially proposed nearly 40 years ago, the level of technology in photovoltaic, power transmission, materials, and efficient satellite design has finally reached a level of maturity that makes solar power from space a feasible prospect. Furthermore, new strategies in methods for solar energy acquisition and transmission can lead to simplifications in design, reductions in cost and reduced risk.

The key architecture needed for such a campaign to be feasible is the use of a distributed network of small satellites to collect solar energy and beam it back to Earth. Most designs for space-based solar power involve launching monolithic self-assembling structures into orbit, which are some of the most troublesome aspects of this concept. As is shown below, the key drivers in this design are the cost of launching satellites in to space and the cost of photovoltaic cells. Both of these costs can be reduced further in the long-run by invoking quantities of scale and learning effects, but remains high cost barriers at this point.

Space power "beaming" is a three step process that involves: 1) conversion of dc power generated by solar cells on the satellite into an electromagnetic wave of suitable frequency, 2) transmission of that wave to power stations on ground, and 3) conversion of the radio waves back into dc power. A great deal of research has been done on the use of microwaves for this purpose. Various

factors that affect efficient power generation and transmission will be analysed in this paper. Based on relevant theory and performance and optimization models, the paper proposes solutions that will help make space-based solar power generation a practical and viable option for addressing the world's growing energy needs.

II. Overall Architecture

The architecture of this system is composed of four components:
- ✓ Solar-Collecting Satellites
- ✓ Inter-Satellite Power Beaming
- ✓ Space-Based Collectors and Beamers
- ✓ Receiving Stations on Earth

By using distributed satellites, each of these components can be distinctly separate from each other, with the exception of the inter-satellite beaming devices, which exist as modules that are installed onto each of the receiving satellites. The design under consideration aims to generate 10 MW of power in space, a nontrivial result that still maintains the smaller scale necessary for a trial case. This design requires 195 satellites spread among 2 central beaming satellites.

The geometry of the distributed satellite system consists of a large power beaming satellite surrounded by 10 sub-beamer satellites that beam the power collected from the collectors to the beamer and are arranged along a circle of radius 350 meters centered on the main beamer. Each of the sub-beamers in turn has line-of-sight (LOS) contact with 12 collector satellites arranged on a circular arc of radius 105 meters. The collector satellites are at least 35 meters apart from each other. This design is to create a redundant array of beamers, ensure LOS for all the collectors, and avoid shadows. The beaming antennae on the collector satellites are have a radius of 2m. Two clusters of up to 120 satellites each will be placed in orbit.
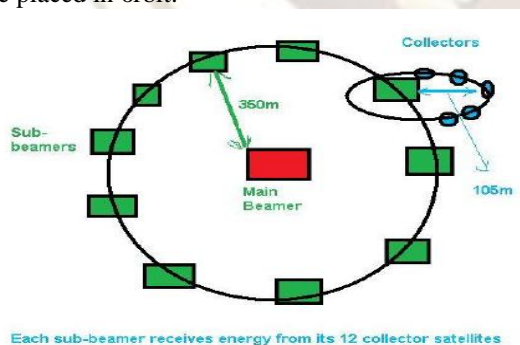

Figure 1 - The Design of an SSP Cluster

A key constraint in a workable arrangement of collector and beaming satellites in a spoke configuration is the possibility of interference among microwave beams. The ideal geometry should negate any destructive interference. Alternatively, beaming events can be scheduled to avoid interference. Power beaming is used at three levels in this design: between collector satellites and the sub-beamers, sub-beamers to beamers, and the main beaming satellite and the ground station. To this end, a higher frequency radiation (5.8 GHz) is used for transmission between satellites and a lower frequency radio-band radiation (2.45 GHz) is used for transmission to a ground station. This satellite constellation is intended for geostationary orbit so that it can remain above a particular ground station and eliminate the need for batteries during eclipse.

The ground station consists of an array of rectennas (rectifying antenna) that capture and convert the incident microwave beam from the space satellite into DC power. The geostationary location of the beaming satellite ensures that the ground station will rarely need to change the orientation of its rectennas. Also, the location of the ground station should preferably be in an area free of electromagnetic interference. The rectenna array at the ground station will be spread over an area of 2 square kilometers.

Another key aspect of the installation of this architecture is that of lifting the satellites into geostationary orbit. To that end, the collector satellites will be designed to utilize ESPA class launch slots, which allow them to share a ride with larger satellites on Atlas or Delta rockets. ESPA refers to the EELV Secondary Payload Adapter standard of the U.S. Department of Defense.
Beaming satellites, being significantly larger, are assumed to launch on Space X's Falcon 9. Given that the number of ESPA slots available will likely remain far too small to support the number of satellites needed to reach orbit, it will be necessary to develop secondary lift capability in-house. Fortunately, ESPA-class satellites can also be launched in bulk on a Falcon 9.

Finally, the development, fabrication, and testing of this design must also be considered in the formation of a business plan. The current design assumes outsourcing of solar array design and assembly; however this work must eventually be brought in-house to significantly reduce cost. In short, this plan assumes a baseline workforce of 300 employees and associated facilities over a time period of 5 years.

The expected pay-off period of this approximately $900M program is about 80 years, using this configuration. Although such a time frame is unacceptable, economies of scale and learning effects leading to new technologies and greater efficiencies can be expected that will reduce payback time, especially with larger versions of the demonstration system proposed.

III. Collection Satellite Design

The purpose of the collector satellites is to capture the sun's energy and convert it into an RF

beam that can be passed either to another similar satellite or directly to a beaming satellite.

In this design, power conversion from solar energy to electricity is done using Copper Indium Gallium Selenite (CIGS) solar cells. These cells, which are being manufactured commercially, are thin-film cells providing 19.5% efficiency. This such efficiency is better than what other thin film cells can provide, but is still much lower than the efficiency provided by triple junction cells, such as those manufactured by Emcore or Spectrolab. These cells are both significantly cheaper and less massive.

Another advantage in using thin-film cells is that they can be purchased in sheets, which can be unrolled when on-orbit. Ordinarily, it is very difficult to deliver spacecraft with large solar arrays on orbit while keeping the solar arrays intact, but thin-film arrays tend to be much less susceptible to damage in loading for launch. It must be noted that the spacecraft's structures and mechanisms are generally limited by launch loading, rather than by in-space constraints. Thin-film cells allow the structural mass fraction of the solar arrays to be reduced significantly. This is important since each satellite will require arrays 25m in length and width. Given that the two key hindrances to a successful SSP design are high power to mass and power to cost metrics, the use of these relatively cheap, mass-producible solar arrays that can be supported with relatively minimal structure is a step forward.

A detailed structural design of the spacecraft is beyond the scope of this paper, but a simplified model was necessary in order to provide the costing model necessary for this paper. The primary requirements on the structure are the ESPA dimensions, which are 35.5"x28"x24". Due to the small space constraints and the relatively high power requirements for the SSP solution being addressed, a significant number of satellites must be deployed to complete the final solar array. A central frame will house the support equipment, such as communications, attitude control, and avionics. A truss will extend from this central bus, providing the supporting structure from which the rolls of solar cells may be uncoiled and extended.

Since each solar cell only captures a small amount of solar radiation, which is primarily the visible spectrum, a significant amount of heat energy is absorbed into the arrays. This excess heat must be radiated into space. The backs of the solar arrays serve as effective radiators since they are always pointing toward deep space. This design proposes a coat of Z93 paint with sufficient emissivity to serve as a reflective surface. Further thermal analysis will be necessary to determine how much of the panels will require painting.

Some amount of the power from the solar arrays will need to be routed to the auxiliary equipment. This will be done with a Maximum Peak Power Tracker,

Lithium Polymer batteries, and the necessary power converters and fuses. It must be noted that, at GEO, the satellite constellation is nearly always in daylight, so a constant input of power means that power conditioning equipment should be minimal.

Attitude Determination and Control is necessary not only to move the satellites from delivery orbit to final configuration but to keep the constellation of satellites in formation. Although launch vehicles can insert very reliably, it will be necessary to make small adjustments in position and attitude. Initial positional changes will be performed with a cold gas thruster system. Station-keeping maneuvers will be performed with a combination of reaction wheels (which can affect attitude) and cold gas thrusters (which can affect position and de-saturate the reaction wheels). Attitude and position determination is performed with an inertial measurement unit, sun sensors, and a GPS receiver.

In order to control the activities of each of the satellites, a powerful network of avionics and communications systems is necessary. Each satellite is controlled by a radiation-tolerant commercial, off-the-shelf flight computer supported by a microcontroller, which serves as an interface host between the board and all sensors, actuators, and communications equipment. Communication with Earth is handled via the central beaming satellites. As a result, communication between collection satellites can be performed at lower power levels and with components of much lower cost and mass. In this design, 802.11 technology in the 5 GHz range, namely 802.11n, will be used. Since the 5.8 GHz band used for inter-satellite beaming is narrow and monochromatic, it will not interfere with communication signals.

The mass breakdowns for each collector satellite can be seen in Figure 2. The power system accounts for most of the mass of each satellite and nearly all of the cost, which supports the theory that a distributed constellation doesn't significantly add to the total mass and cost of the system.
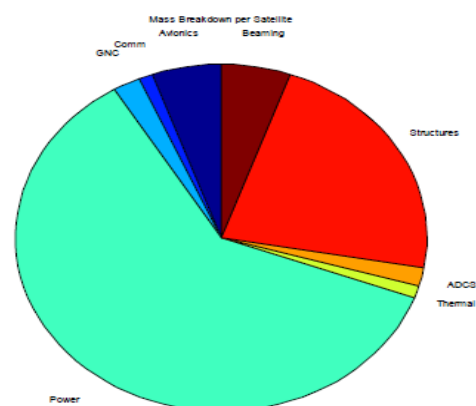

Figure 2: Mass Breakdown for Collector Satellite

IV. Beaming Satellite Design

The beaming satellites serve as the hub for both the in-space power and communications grids. For power, they collect the energy being relayed from each of the collectors/sub-beamers and redirect that energy toward Earth using a much more powerful rectenna array that has a considerably large area. For communications, the beaming satellites relay signals not only between the different spokes of the system, but also decipher which telemetry and commands must be relayed to and from the Earth.

The most prominent feature of the beaming satellite is the downlink rectenna array. In the system proposed, each collector satellite beams its power to one rectenna array slot. This one-to-one correspondence is designed to minimize interference between the beams of individual collector satellites. The rectenna array on-board the beaming satellite is similar to the one at the ground station, except for the fact that it is optimized to collect beams of a higher frequency and hence is smaller in size. The support equipment of the beaming array is, in fact, very similar to that of the collection satellites. The notable exception is that less structural support for solar arrays is needed. Due to the large size of the collection array, however, the beaming satellites are significantly larger than the collection satellites.

The communications equipment aboard the beaming satellites must be more sophisticated to ensure that it can provide sufficient relay capabilities and downlink to Earth. Moreover, the reliability of components on the beaming satellite must be significantly higher (with redundant components on-board) since a loss of capability on a beaming satellite would cripple the grid.

V. Power Beaming Between Satellites

The power beaming between satellites will take place at a higher (5.8Ghz) frequency, to ensure that the rectennas on board are smaller and that there is no interference with beaming to the ground. The power conversion efficiency at this stage is assumed to be up to 70%. The photovoltaic DC to microwave conversion efficiency is 83% [1] and the microwave to DC conversion at the rectenna of the sub-beamer is around 85%[2]. (McSpadden et al achieved a DC conversion efficiency of 82% for 5.8 GHz rectennas in 1998, [8]) DC to microwave conversion is accomplished through magnetrons or similar devices. Semiconductor devices like various field-effect transistors do not provide comparable efficiency at this point – it is generally below 50%. [3]. The collector satellites will transmit their power to the beaming satellite and the geometry of the satellite cluster ensures that the beams don't interfere with another collector's beams. Occasionally, inter or intra spoke beaming can be used for station-keeping or for changing the orientation of satellites within the cluster.

Another aspect of power beaming between satellites is the re-use of wasted power during transmission. It has been shown that ambient microwave energy can be reused by a rectenna array with an efficiency of 20% (up to 60% in certain cases) [4]. This recycled energy can be specifically used for the station-keeping needs of the satellite cluster. The incorporation of this feature would be an optional measure for squeezing out maximum overall efficiency from the system.

VI. Power Beaming from Space to Earth

The efficiency for power transmission through free-space has been shown to approach 100% and its dependence on various factors can be characterized by the following dimensionless quantity [7]:

$$X = \frac{2\pi R_t R_r}{Z\lambda}$$

R_t = Radius of transmitting antenna
R_r = Radius of receiving antenna
Z = distance
λ = wavelength

This result is derived by treating electromagnetic beams as Gaussian beams, [9], [10]. Experimental results, in [2], about the relationship of efficiency with X/2, clearly support the theoretical predictions of the Gaussian beam model. The Gaussian beam used in this design will have a power tapering (ratio of power density at the center of transmitting antenna to that at the edge) of 10-15 db.

The area of the rectenna arrays in space and on the ground will be optimized according to this relation. In this design, the total transmitter aperture in space is ~0.8 km2 and the rectenna array occupies ~1.5 km2 on earth. The main beamers have huge transmitter antenna arrays, which span the overall geometry of the satellite network.

The 2.45 GHz frequency range has been widely studied for the purpose of space solar power transmission. This frequency is thought to be optimal both in terms of efficiency and transmission. A power conversion efficiency of up to 85% has been obtained by rectennas operating at 2.45 GHz. [5] This region of the electromagnetic spectrum is also free from the effects of attenuation in the atmosphere, thereby making the SSP system immune from the effects of weather. Attenuation begins to affect transmission after 3GHz and spikes afterward, making the 2.45 GHz region our best choice for SSP. [6]. Studies by [7] have shown that power loss in the atmosphere is less than 1% for this frequency. A rectenna array on the ground converts the microwave energy into DC power, which can then be converted into AC and fed to the power grid infrastructure on Earth.

VII. Launching System into Space

Launching the SSP constellation into orbit is one of the most difficult aspects of the program. Launch vehicles are expensive, operationally difficult to use, and provide a harsh environment for the health of transported satellites during launch. Some aspects of this architecture, however, help to mitigate these problems:

✓ A large number of small satellites can fit into a single launch vehicle.
✓ Modularity of the system means scope can be expanded or reduced to fit available launch vehicle payload capabilities.
✓ The lack of a monolithic structure eliminates the need for Saturn V or higher-class heavy-lift launch vehicles.

This architecture calls for designing spacecraft to fit the EELV Secondary Payload Adapter standard. The ESPA Program is sponsored by the DoD Space Test Program and provides secondary rides to orbit for 180 kg vehicles at a cost of about $1M each. It must be noted that use of ESPA is not viable in the long term due to the limited number of ESPA rides available on a regular basis, but this approach serves as an optimal way to prove out the initial steps of the system. ESPA type adapters can be developed to launch as many as 25 satellites at a time on a Falcon 9 or similar rocket. Due to the larger size of the beaming satellites, they will be launched on Falcon 9 or similar launch vehicles; it is expected that two beaming satellites (and collecting satellites if space and mass allows) will fit on each Falcon 9 launch. Space X vehicles are base lined due to the significantly lower cost over other providers and the likely further reductions available once reusability is incorporated into the design

VIII. Design and Development Costing

Often neglected in initial trade studies, the cost of design and development must also be considered. In this paper, this aspect is analyzed in terms of employees and facilities. First, it is assumed that development work will be performed by 300 engineers, management, fabrication, test, and support staff over a period of 5 years. These people will operate a facility that will be used for design and manufacture at a rent of $2M per year and will require about $30M of startup cost for machinery, tooling, office supplies, etc.

IX. Conclusion

The overall efficiency of this distributed satellite array of collectors, beamers and sub-beamers is 49%, but the overall return on investment is much higher as modularity allows one to put in a large swarm of low-cost satellites in orbit to generate a higher power output.

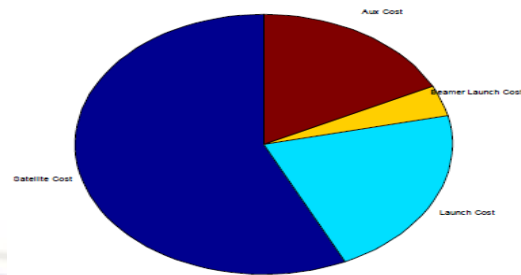The breakdown of cost from a campaign perspective can be seen in Figure 3

Figure 3: Campaign Cost Breakdown

Given recent advances in microwave beaming and DC to microwave conversion and vice versa at high efficiency rates, falling launch cost for satellites, and the operational robustness of the distributed architecture of solar power satellites proposed here, the time has come to phase out our dependence on fossil fuels and incorporate SSP power into Earth's electrical grids.

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