**Proceedings of the ASCE Earth&Space 2006 Conference, League City, Texas, April 2006**

# Space Power Grid- Evolutionary Approach To Space Solar Power

N. Komerath, N. Boechler, S. Wanis
School of Aerospace Engineering and Center for International Strategy, Technology & Policy, Georgia Institute of Technology, Atlanta, GA 30332-0150
PH (404)894-9622; FAX(404)894-2760; email: komerath@gatech.edu , gtg218s@mail.gatech.edu, sw87@mail.gatech.edu

***Abstract***
Different technological options are presented for an evolutionary architecture towards space-based solar power. The space power grid approach integrates the issues of global warming and energy demand with the technologies for space-based solar power. In the first stage, a constellation of satellites in low earth orbit will transact power exchanges between earth-based power plants. In a second stage, solar energy will be collected and directly converted in low earth orbit to microwave or laser beams. In the final stage, low-mass collectors will focus sunlight on the converters in low earth orbit, opening up large-scale power generation from space with an established ground infrastructure. The system has the potential to enhance the commercial viability of solar and wind-based power plants on earth, by opening markets around the world to smoothen fluctuations in supply and demand.

**Introduction:** This paper presents architecture options for an evolutionary approach to the dream of Space Solar Power. Since the 1970s, Space Solar Power (SSP) has offered the utopian promise of abundant, clean, renewable energy, beamed down as microwaves from space or from the Moon, to collectors on Earth. The promise of unlimited power remains distant because of the huge cost of sending photovoltaic arrays to geosynchronous orbit (GEO), or building them on the Moon. At the same time, concerns about global warming on Earth are driving stringent regulations on CO2-generating power plants, and posing large imminent economic costs to the United States. In this paper, we describe an architecture and a conceptual design of a system with a startup mechanism and a viable transition path to SSP aligned with market needs. Difficulties with SSP concepts are: the need for huge reductions in launch cost [1,2] the lack of an evolutionary approach (cost to first power >$300B), and a lack of urgency [3].

Current launch cost to GEO is $13000 to $25000 per kg, and the mass of conversion equipment from DC to microwave is on the order of 1kg/kw. Proponents of locating solar-power plants on the Moon argue that this would be cheaper as much of the mass of the system can be located on the Moon and perhaps even come from lunar materials rather than being built in Space. Some have argued that the 5000-odd heavy–lift launches to GEO needed for SSP would bring mass-market economies and collapse the launch cost. There is little evidence to back this.

Recently, the Japanese Aerospace Exploration Agency has developed an evolutionary model for Space solar power. Their approach is still to launch satellites with collectors and converters to GEO, but to enable this to be done in small increments using a compact modular design, so that first power and revenue generation commences on a small scale. The system can then be expanded by adding more modules to the power generation platforms. A prism-type collector is combined with modules that convert the power to beamed microwave. This is also compatible with the direct-conversion laser discussed later. This is thus an elegant scaleable design; however, the cost per unit power is still quite high because all elements are at GEO.

Our approach is to turn the SSP concept inside out. We see the initial role of Space as the power grid to exchange power between terrestrial generators and consumers. Thus the initial cost recovery is through saved transmission line costs and vastly improved reliability, smoothness and market reach of power output from alternative energy plants. Currently, it is not possible for new power plants based on "green" technology to compete with the low costs of the established power industry. There are two reasons for this. The first is the established landline grid, laid at a time when land prices were far lower, and long-since recovered. New plants using solar or wind energy will face much tougher regulations and higher costs. Secondly, the nuclear power industry has amortized its high initial costs, and is not set to compete aggressively with very low recurring costs. In the Space Power Grid approach, wind and solar plants would be located where suitable (high deserts or equatorial regions) and would exchange power through space with counterparts in distant countries. This would help them become reliable, primary power generators with plenty of reserve capacity for emergencies. The lower efficiency of space transmission would be partly compensated by the amortized savings in transmission line land and equipment costs, but the real benefit comes from being able to sell power in markets where they fetch far higher prices than could be obtained in local markets, especially in the United States. The space power grid also has obvious implications for emergency preparedness, enabling power to be delivered to disaster-stricken areas swiftly using airlifted ground receivers.

Coupled with current environmental policy issues, this approach enables rapid growth of the "green" energy generation industry, paving an intermediate solution path towards a viable solar power industry that integrates extraterrestrial resources. Once this infrastructure is created, transition to space-based or lunar-based sources is simpler – in other words, this provides the evolutionary approach that has been lacking to-date. The first iteration of the system is described in Boechler et al.[4]

In the long term this will open up a technological solution with far-reaching consequences for energy independence, increase of "green" energy sources, and enabling benign economic development in areas where such development is not now viable. It also sets the context for technological breakthroughs in efficiently converting solar power directly to beamed energy. This is a prospect with a multitude of applications.

**Conceptual Design:** Our proposed system in its present version consists of 36 to 180 satellites in 1200km-high orbits, (as opposed to the 42,000 km GEO orbits of SSP), trading energy through beamed microwave power. Each satellite carries a low-mass 140 GHz antenna, with wave guides to 4 high-power and 100 low-power transmitters. Each can transmit along line-of-sight to 4 other satellites, and 100 customer sites, distributing microwave beamed power from up to 3 earth-based stations totaling up to 200MW per satellite. Our cost estimation shows that such a system can be made economically viable using the savings from transmission costs, and the better prices obtainable through global market reach. Investing a small fraction of $CO_2$ reduction credits can be used to grow the industry. We solve the terrestrial economic dilemma of generation versus distribution by beaming energy into space from ideal collection locations, and bouncing it off lightweight reflectors to earth-based microwave collectors for local distribution. The next step, as the first generation of satellites are replaced in roughly 15 years, is to incorporate new technology for direct conversion from broadband sunlight to microwave. The efficiency and mass per unit power of this technology is one of the key thrust areas for research and development. These newer satellites would have solar collectors sized to accept high intensities of solar energy. This generation of satellites would add a small amount of energy to the grid. The final step in the SSP system is to launch lightweight thin-film reflectors to deploy in high orbits, and focus sunlight using tracking mirrors or Fresnel lenses onto the collectors on the LEO satellites. This step obviates the need for putting massive solar converters in GEO or other high orbits, while avoiding the issues in transmitting visible or air-absorbed wavelengths into the atmosphere. The solar energy would then flow into an infrastructure and market acceptance that would already be in place to receive such power. The incremental cost of these satellites is small, and comes after the system is generating revenue from energy transactions.

The presentation of the paper describes the conceptual design of the overall system. The mass and cost targets for a 20-year full return of investment at current Treasury Bond Return on Investment, are shown to be well within reason. The terrestrial part requires little new technology. The international policy issues and opportunities related to acceptance of such a system are also discussed. Current results show that there are good technical solutions to all of the various technical issues raised by reviewers and other experts. New advances in microwave wave guides for beam weapons, direct energy conversion, high-speed digital signal processing for "smart" adaptive antenna arrays, and low-mass active heat-exchanger technology, all play a role in enabling such a system in the not-too-distant future. However, the true viability of the system comes because it takes account of new realities in public policy issues related to energy and international concerns about the use of and participation in, Space.

Table 1 shows three possible architecture options for the Space Power Grid. The first is simply the Space Power Grid phase. Here there are two types of satellite designs: The first type is a constellation of distribution satellites, whose function is to receive power from the ground and/or other satellites, and send it to other satellites or to receivers on the ground. In later years, as these age and are replaced, the next generation of satellites will have an array of solar cells tuned to certain ranges of wavelength, so that they have high conversion efficiencies to microwave power from sunlight in those ranges, without the attendant heat rejection problem of broad-band cells. This would add only a small amount of power to the grid.

In the second stage of the architecture, there are 3 possible options for adding more power to the grid. The first is to use conventional photovoltaics on the LEO satellites, perhaps with large-area collectors attached to them. The collection efficiency would be lower than with GEO satellites that can receive power continuously, but this has the advantage of having the ground infrastructure already in place for synchronized beaming.

At a higher level, a direct solar-pumped laser could be used to convert solar energy on the LEO satellites, and transmit the laser beams to other satellites where the demand for power is greater (e.g., satellites over the dark side of earth). Recently, development of such lasers has reached a stage where efficiency of up to 38% has been shown[5]. These satellites would receive incoming laser energy using their high-efficiency narrow-band photovoltaic cells, convert it to microwave, and beam it to Earth. This architecture has two advantages: the beaming to Earth could be done at optimal microwave frequencies for maximum transmission through the atmosphere, without requiring excessive transmitter size. The laser beams would propagate with very high efficiency, and require only small collectors. Thus the mass and overall cost per unit power of the system with this architecture may be substantially lower than the lower-risk option presented before.

Option 5 is a solar-pumped MASER that produces microwave beams directly from broadband sunlight. While direct-solar-pumped Masers were investigated in the 1960s, and moderate efficiencies were shown, little work has been found on this topic recently. Given the new developments in direct solar-pumped lasers, the question is worth reopening. Issues of shifting frequency to sub-harmonics must be resolved. Should this become feasible at high conversion efficiency, the system mass per unit power can be brought down considerably.

Option 6 is the most futuristic: this is to use direct conversion from sunlight to beamed microwave using an optical rectenna. An optical rectenna is a device that has antenna elements built to receive the shortest wavelengths of interest in sunlight, and has enough of them spaced over a large area to be able to also tune in to the largest wavelengths of interest. The basic issue in making such rectennae is to develop fabrication techniques that can handle the nanometer-scale resolution needed for the energetic frequencies of sunlight. In theory, should this work, extremely high efficiency conversion can be achieved, and the system mass can be quite small.

**Table 1: Possible Architecture Options**

| | Satellite Location | Transmission Frequency | Transmission Target | Receiving Frequency |
|---|---|---|---|---|
| **Space Power Grid Phase (GND->LEO->LEO->GROUND)** | | | | |
| 1. Distribution Satellite | LEO | Microwave | Ground/LEO | Microwave |
| 2. Distribution Satellite + tuned solar cells | LEO | Microwave | Ground/LEO | Microwave+Narrowband Optical |
| **Space Solar Power Phase (GEO/SUN->LEO)** | | | | |
| 3. Conventional Photovoltaics | LEO | Microwave/Narrowband Optical | LEO - 1 or 2 | Sunlight |
| 4. Solar Pumped Laser | LEO | Narrowband Optical | LEO - 2 | Sunlight |
| 5. Solar Pumped Maser | LEO | Microwave | LEO - 1 | Sunlight |
| 6. Optical Rectenna + Direct Conversion | LEO | Microwave/Narrowband Optical | LEO - 1 or 2 | Sunlight |
| **Full Space Solar Power (SUN->GEO->LEO)** | | | | |
| 7. Sun Sats - Reflector | GEO | Reflected Sunlight | LEO SSP Sats (3-6) | Sunlight |

In the final phase of the architecture, the system would go to full Space Solar Power, generating much more power than is beamed up in transactions between earth-based entities. In this phase, large lightweight reflectors or prism / Fresnel lens arrays would be constructed in GEO or beyond, to collect and redirect sunlight onto the LEO craft, where the converters would reside.

Thus the GEO launch cost per unit sunlight power collected would be minimal compared to present concepts where the massive conversion equipment must be located at GEO. These would fit with the LEO architecture options already discussed, but require either a profusion of LEO satellites, or a large increase in the power-handling capability of the LEO satellites in the next generation. The point made however, is that the architecture is amenable to gradual buildup. It also allows augmentation with new satellites, collectors and new technology, over time, but permits revenue generation at a healthy level from the point at which the first few satellites are launched, and a set of roughly 20 ground stations come up around the equator.

**Conclusions.** This paper follows up on the initial concept of a Space Power Grid as the first step of an evolutionary path to commercially viable space solar power. It succinctly gives the different technology options that are either available today, or are on the horizon, in developing architectures for the Space Power Grid.

**Acknowledgments.** The first author (NK) and third author (SW) acknowledge support through Sam Nunn Security Fellowships provided through the School of iInternattional Affairs at Georgia Institute of Technology, made possible through a grant from the MacArthur Foundation. The second author (NB) is supported through an NIAC Student Fellowship from the NASA Institute of Advanced Concepts.

***References***

[1] Schwartz, R.J., et al, (2001) "NASA's Space Solar Power Exploratory Research And Technology (Sert) Program". Strategy. National Academy Press 2001. http://www.nap.edu/execsumm/0309075971.html (viewed Nov. 18, 2005)

[2] Smith, A.,(2003) "The Case for Solar Power from Space". Aug, 2003. http://www.nsschapters.org/ny/longisland/articles/SSPCase.html#note1 (viewed Nov. 18, 2005)

[3] McSpadden, J.O., Mankins, J.C., (2002) "Space Solar Power Programs and Microwave Wireless Power Transmission Technology". IEEE Microwave Magazine, Dec. 2002. pp. 46-57

[4] Nicholas Boechler, N., Hameer, S., Wanis, S., Komerath, N., "An Evolutionary Model for Space Solar Power". STAIF 2005-082, Proceedings of the Space Technology and Applications International Forum, Albuquerque, NM, February 2006.

[5] Saiki, T., Motokoshi, S., "Development of Solar-Pumped Lasers for Space Solar Power". IAC-05-C3.4-D2.8.09, 56th International Astronautical Congress, Fukuoka, Japan, October 2005.